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THESIS

A SIMPLE INTERACTIVE PROGRAM TO DESIGN SUPERCAVITATING PROPELLER BLADES

by

Marc B. Wilson

June 1982

Thesis Advisor: D. M. Layton

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A self-contained, rapid, Computer Aided Design (CAD) program for a desk top computer (i.e. HP 9845) was developed for a first cut approximation for the design of a supercavitating propeller blade. This program eliminated the error-prone, tedious interpolation of empirical data graphs by providing approximations and curve fitting techniques to augment existing formulae. The complex Goldstein function and the inexact Prandtl approximation were replaced by a more simple

#20 - ABSTRACT - (CONTINUED)

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A Simple Interactive Program to Design Supercavitating Propeller Blades

by

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Lieutenant, United States Coast Guard
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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ABSTRACT

A self-contained, rapid, Computer Aided Design (CAD) program for a desk top computer (i.e. HP 9845) was developed for a first cut approximation for the design of a super-cavitating propeller blade. This program eliminated the error-prone, tedious interpolation of empirical data graphs by providing approximations and curve fitting techniques to augment existing formulae. The complex Goldstein function and the inexact Prandtl approximation were replaced by a more simple function, the Wilson factor, that maintained the confidence level of the manual calculations.

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TABLE OF SYMBOLS

A - Area, generally

A_D - Developed blade area

A_E - Expanded blade area

A_0 - Disk area

C_D - Drag coefficient

C_L - Lift coefficient

C_Q - Torque coefficient

C_T - Thrust-load coefficient

c - Blade chord length

D - Propeller diameter, assumed

D_{opt} - Propeller diameter, optimum

F - Blade force

F_H - Transverse force, Horizontal

Fn - Froude number

g - Gravitational acceleration

h - Pitch Correction Coefficient

J - Advance coefficient

J_{opt} - Advance coefficient, optimum

L - Ship length

L - Lift

M - Blade moment

N - RPM

P - Pitch of propeller

p - Pressure

Q - Propeller torque

q - Dynamic pressure
R - Propeller radius
Re - Reynolds number
RPM - Revolutions per minute
S - Submergence
T - Propeller thrust
t - Thickness of blade section
V - Linear velocity
V_a - Speed of advance
x - Percent radius
z - Number of blades
α - Angle of attack
α_1 - Cavitation correction
α_2 - Lifting surface co-rection
β_i - Angle of hydrodynamic pitch
ε - Drag/Lift Ratio
η - Propeller efficiency
λ - Advance Ratio
κ - Goldstein Factor
ν - Kinematic viscosity coeff.
ρ - mass density of fluid
σ - cavitation number
Γ - circulation

ABBREVIATIONS

BAR - blade developed area ratio, A_D/A_0
BTF - blade thickness factor

BWR - blade width ratio, (maximum blade width)/D

EAR - expanded blade area ratio, A_E/A_O

MWR - [A_D/length of blades (outside hub)]/D

NSRDC - Naval Ship Research and Development Center

SUBSCRIPTS

h - load component due to hydrodynamic force

x,y,z - load components acting in the direction of x,y,z axes, respectively.

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I. INTRODUCTION

The screw propeller was first developed by an Englishman, Hooke, in the 17th century, but received little use until nearly two centuries later. In the late 1800's, while the British steamer TURBINIA was being designed, it was first observed that the propeller could operate in a cavitating mode wherein at least a portion of the propeller operated in an 'air cavity'. This air cavity was not air but a result of critical pressure conditions in the vicinity of the propeller blades [1].

Inasmuch as propeller cavitation usually results in marked increases in required rotational speed, propeller slip, and erosion of the blade surfaces, as well as decreases in the power efficiency, cavitation was to be avoided, if at all possible. One precaution was to insure that the tips of the blades were always well submerged to as not to have an air interface. If partially submerged then ventilation may result yielding similar effects as cavitation.

It was not until the mid-twentieth century, while searching for drive systems for racing boats, that it was discovered that by operating in extreme cavitation regions, high watercraft velocities could be obtained with but minimal deleterious effects. In fact, not only could the propeller be operated in a cavitating mode fully submerged, but it could also be operated with a portion of the blades out of the

water partially submerged. As a result, these systems are referred to as either fully submerged or partially submerged propellers. With either propeller the effect is essentially the same although the loads may differ.

Whereas the design techniques for conventional propellers had become well established [1], few techniques were available for the supercavitating blades or foils. In general, the subcavitating design procedures were used as an approximation, but this left much to be desired. In the mid-1950's, Tulin [1] proposed two-dimensional lift-drag characteristics for these designs, and at the same time Morgan and Tachmindji applied circulation, or lifting line, theory. The latter techniques were based on the works of Prandtl, Hemhold, Goldstein and Lerb, utilizing hydrodynamic principles. Now, nearly thirty years later, these approaches are still used in the design of supercavitating propellers [1].

The most rigorous of these techniques is Lerb's [2] induction factor method, while the use of the Goldstein function, though less precise, compares quite favorably to Lerb's method. Any of the methods used in the design of supercavitating propellers have been labor intensive [2].

A. STATE-OF-THE-ART

The formal design methods for high speed naval ship propellers were established by Morgan and Tachmindji of the David W. Taylor Naval Ship Research and Development Center (NSRDC) [6], using the Goldstein function to correct for

supercavitating operations. The major problem in these techniques was attributed to blade cavity effects, and a correction in the form of an accountability factor is used to offset this effect. This correction is based on an approximate cavity thickness in the lifting surface calculations.

Another approach in the design method is that taken by Hydronautics, Inc., [1] that utilizes lifting-line theory and the Goldstein function together with a camber correction factor and two-dimensional foil analysis about a free surface.

A comparison of the two approaches by Tulin indicates an overestimation of efficiency and thrust by the NSRDC method [1]. Both methods rely heavily on the use of empirical data and require frequent interpolation and extrapolation of data. Most of the more recent research in this field has been conducted between 1955 and 1975, and the confidence level in the selection of a supercavitating propeller without full-scale testing has been unfavorable.

B. FUNDAMENTALS OF CAVITATION

The phenomena of cavitation is the formation of bubbles about a foil or blade. This can be explained by the Bernoulli equation, assuming inviscid compressible behavior, where the sum of the static pressure, p, and the dynamic pressure, $\frac{1}{2}\rho V^2$, is a constant.

$$P + \frac{1}{2} \rho V^2 = p_t = \text{constant} \qquad (1)$$

where:

p = static pressure on the foil downstream side,

V = velocity of the flow,

ρ = density,

p_t = total pressure (total head).

By relating the constant total pressure of the ambient conditions (subscript 0) to the constant total pressure at any point, assuming constant density,

$$p + \frac{1}{2}\rho V^2 = p_0 + \frac{1}{2}\rho V_o^2 \qquad (2)$$

By combining the dynamic pressure terms, it can be observed that the pressure at any point may be expressed as,

$$p = p_0 + \Delta p \qquad (3)$$

If $p = 0$, so that $p_0 = -\Delta p$, the fluid changes state and cavitation results. In reality, the static pressure does not completely reach zero, but will decrease to the vapor pressure of the fluid, p_v. When the static pressure reaches this value,

$$p = p_v = p_0 + \Delta p \qquad (4)$$

the fluid 'tears' or boils. This is cavitation! See Figure 1.

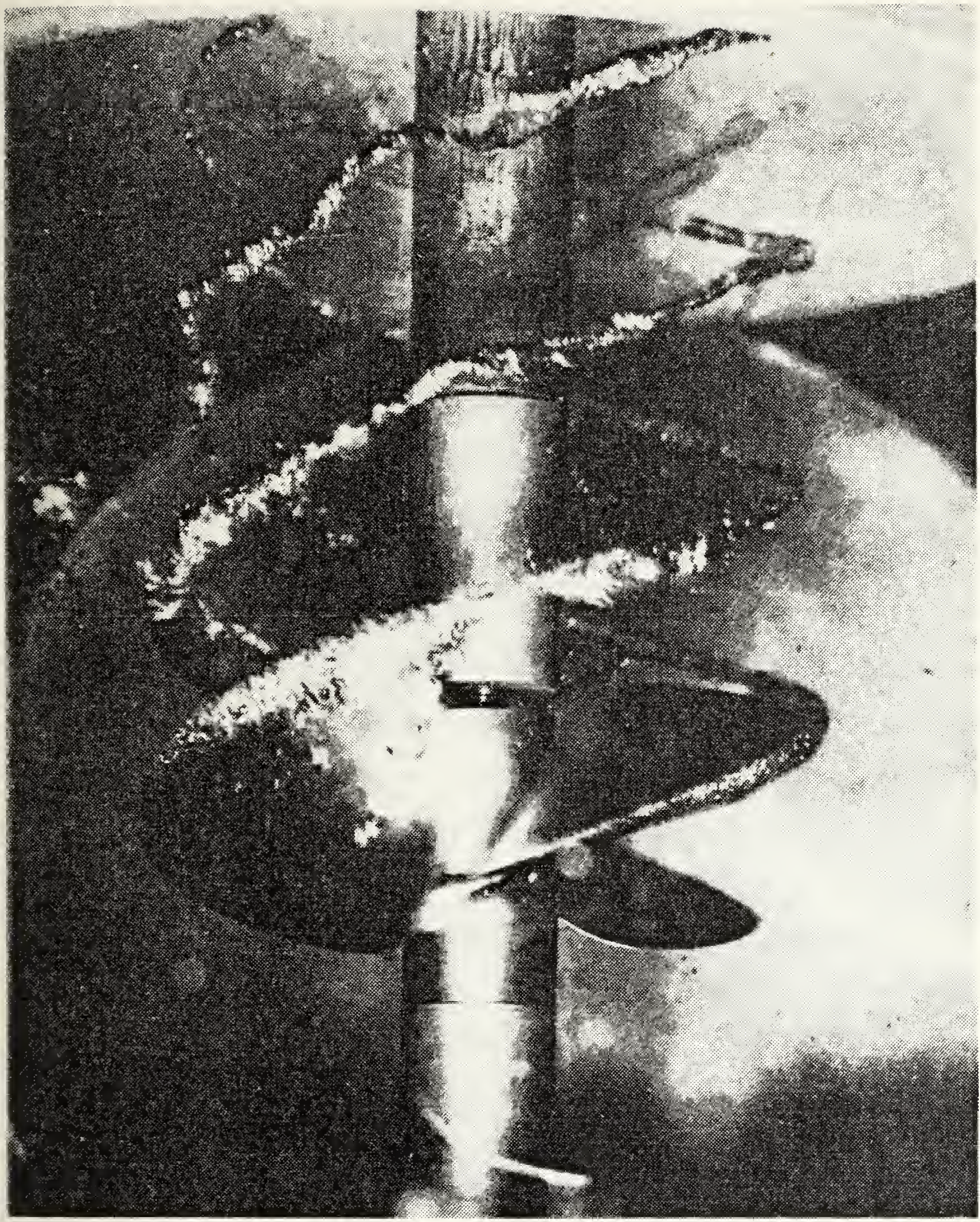


Figure 1. Picture of a Propeller Blade Tip Cavitating (NSRDC)

A measure of the amount of cavitation, called the cavitation index or the cavitation number, is determined by dividing the pressure change, Δp, by the dynamic head of the flow.

When the bubble formation that commences at the leading edge extends beyond the trailing edge, so that a plume appears to form downstream, the foil is said to be supercavitating.

C. SUPERCAVITATING PROPELLERS

A propeller designed for optimum non-cavitating or subcavitating operation cannot perform efficiently in a cavitating environment, and if it is desired to have a propeller system that can utilize the high speed advantages of the supercavitating propeller, a special design of the foils must be accomplished that will deliver thrust efficiently in a quasi-gaseous environment. When it is not operating in a supercavitating environment, there is no real advantage to this type of propeller system, as shown in Figure 2.

One can visualize a supercavitating propeller as somewhat a hybrid operating between the marine and the air environment, and it has somewhat the appearance of a stubby propeller of an aircraft rather than looking like a conventional marine screw.

Current design techniques, as outlined in Chapter II, call for extracting values from empirical curves to use in the calculations. It is the purpose of this project to semi-automate this process, as outlined by references 1, 2, and 3.

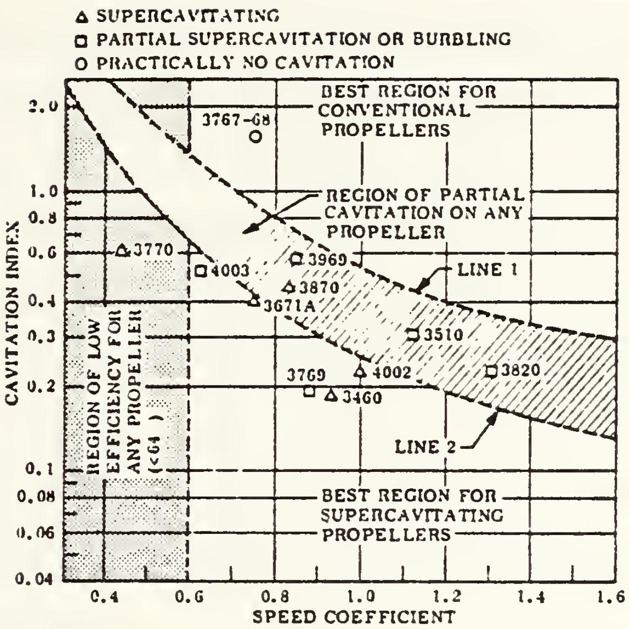


Figure 2. Practicability of Supercavitating Propellers, Showing Model Numbers of NSRDC-Tested Model Propellers [1]

II. BASIC DESIGN METHODOLOGY

The criteria for use of the supercavitating propeller is essentially the relationships between the speed of advance, V_a, the rotational velocity, RPM, and the cavitation number, σ.

As in any design problem, the first requirement is the establishment of the design operating point for which parameters are assumed, known or desired. Such a point may be a speed condition, such as cruise, hump, maximum or patrol velocity, or it may be a power condition. There are several basic parameters that are unusually well known or can be readily assumed. These include the velocity of the craft, resistance (drag), power available, speed of advance (or wake factor), thrust (or thrust deduction factor), number of blades and submergence.

As a first-cut approximation for the required diameter of the propeller, the Burtner equation is used [1],

$$D = [50 \times (HP)^{0.2}/RPM^{0.6}] \text{ ft} \qquad (5)$$

The thrust is non-dimensionalized by the use of a coefficient of thrust, C_T,

$$C_T = \frac{T}{\frac{1}{2}\rho V_a^2 A S} \qquad (6)$$

where:

T = thrust (lbs)
ρ = density (slugs/ft^3)
D = propeller diameter (ft)
V_a = speed of advance (knots)
S = submergence
A = disk area (ft^2)

The speed of advance is also non-dimensionalized to an Advance Coefficient, J,

$$J = 101.34 \times V_a/(\text{RPM} \times D) \qquad (7)$$

where 101.34 is the conversion factor in terms of ft. and sec.

The above factors are shown in pound-force, pound-mass, and feet units, but the entire calculations can also be accomplished in metric units, if desired.

Once C_T and J are determined, the expected efficiency is obtained from empirical data, usually plotted as J versus $\sqrt{C_T}$. The radial distribution of pitch is determined from Kramer Thrust Coefficient Curves, with inputs of their Advance Ratio, λ, and the Ideal Thrust Coefficient, C_{Ti}, where

$$\lambda = V_a/(N \times D \times \pi) \qquad (8)$$

and,

$$C_{Ti} \cong 1.07\ C_T \tag{9}$$

It is to be noted that only approximate values are used inasmuch as the exact value of C_{Ti} is,

$$C_{Ti} = C_T/(1 - 2\,\varepsilon\,\lambda_i) \tag{10}$$

where:

ε = drag to lift ratio

λ_i = ideal advance ratio.

At this point, solutions can be made for the radial pitch, $(D \times \pi \times \lambda_i)$, and the hydrodynamic pitch angle, β_i.

Once the hydrodynamic pitch angle, β_i, is established, the ideal delivered thrust coefficient, C_{Ti}, may be determined by using the more rigorous induction factors and numerical integration (Simpson's Rule), or by using the Goldstein function, κ, [5]

$$\kappa = \frac{z\,\Gamma\,N}{2\,\pi\,u_a\,V_a} \tag{11}$$

where:

Γ = circulation

u_a = axial velocity.

The delivered ideal thrust coefficient, C_{Ti}, is compared to the required value of C_{Ti}, and if the delivered value is

less than the required value, the hydrodynamic pitch angle, β_i, is corrected and the problem iterated until the delivered value of C_{Ti} is equal to the required value. If the iteration process becomes too cumbersome or too lengthy, interpolation may be used to validate the new value of β_i.

At this point the designer can compute the geometric properties of the blade, first by computing the value of $C_L(\ell/D)$, where,

$$C_L = L/(\tfrac{1}{2}\rho V^2 A) \tag{12}$$

ℓ = blade width

L = lift

and then by determining the blade width at seventy percent of the blade span,

$$\ell_{0.7} = \frac{C_L(\ell/D)_{0.7} \times D}{C_\ell} \tag{13}$$

where:

C_ℓ = coefficient of lift for a finite foil.

Reference 2 states that the optimum value for C_ℓ is 0.16 and that value is used in these computations.

A recommended distribution of section chord as a function of the chord size at the seventy percent span [2], is shown in Table I.

TABLE I

RADIAL DISTRIBUTION OF CHORD

0.400	1.088
0.475	1.086
0.550	1.073
0.625	1.046
0.700	1.000
0.775	0.903
0.850	0.763
0.925	0.565
1.000	0.000

At each radial station, the blade shape may then be determined, as shown in Figure 3.

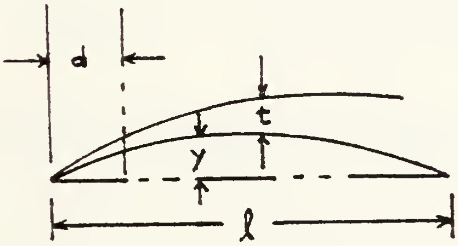


Figure 3. Blade Dimension Sketch

From the hydrodynamics of lifting surfaces and empirical data, the maximum dimension, $(y/\ell)_{max}$, is [1],

$$(y/\ell)_{max} = 0.1553\ C_L - 0.00462\ \alpha$$

where the angle of attack, α, is a function of the lift coefficient.

The height-to-chord ratio is then corrected by using camber correction factors, k_1 and k_2, are functions of the expanded area ratio, EAR, which is the ratio of the expanded blade area, A_E, to the disk area, A_0,

$$EAR = A_E/A_0 = \frac{2z}{\pi} \int_x^1 \frac{\ell}{D}\, dx \tag{14}$$

The EAR is similar to the BAR blade developed area ratio with the difference being that the EAR is with respect to radial distribution.

The corrected thickness factor, $(y/\ell)_c$, is,

$$(y/\ell)_c = k_1 k_2 (y/\ell)_{max} \tag{15}$$

The thickness of the blade section, t, is determined from,

$$t/\ell = F'C_L + N'\alpha \tag{16}$$

where F' and N' are as shown in Table II [1].

TABLE II

THICKNESS COEFFICIENTS [1]

d/ℓ	y/y_{max}	F'	N'
0.0000	0.0000	0.00000	0.000000
0.0075	0.01888	-0.001326	0.001254
0.0125	0.03244	-0.002574	0.001870
0.05	0.14189	-0.016816	0.005704
0.10	0.29150	-0.039520	0.010074
0.20	0.56636	-0.078940	0.017349
0.30	0.78458	-0.097600	0.022222
0.40	0.93187	-0.092870	0.024647
0.50	1.00000	-0.071780	0.025710
0.60	0.98340	-0.037750	0.025853
0.70	0.87797	0.005940	0.025605
0.80	0.68055	0.056880	0.024660
0.90	0.03886	0.112090	0.023047
0.95	0.20650	0.139620	0.022048
1.00	0.00000	0.166950	0.020937

The final step in determining the geometric parameters is the determination of the corrected pitch-to-diameter ratio, P/D, using as inputs friction, cavitation and lifting surface theory. The friction is considerably small and may usually be neglected, and the pitch-diameter ratio may be given as,

$$P/D = x \times \pi \times (1 + (\Delta(P/D)/(P/D)) \times \tan(\beta_i + \alpha_1)) \quad (17)$$

where:

$$1 + (\Delta(P/D))/(P/D) = (\tan(\beta_i + \alpha_1 + \alpha_2)_{0.7})/\tan(\beta_i + \alpha_1)_{0.7} \quad (18)$$

$$\alpha_1 = 57.3\, K_\sigma(0.0849 \times C_L + 0.0152 \times \alpha) \quad \text{(in degrees)}$$

$$\alpha_2 = \alpha_b + (\beta_i - \beta) \times (2/(1 + \cos^2\beta_i(\tfrac{2}{h} - 1)) - 1)$$

h is the pitch correction factor, and α_b is the vortex correction factor (may be neglected due to its magnitude).

K_σ is a function of the cavitation index at the seventy percent station, $\sigma_{0.7}$, which is in turn,

$$\sigma_{0.7} = 2 \times g \times H \times J^2/V_a^2\,(J^2 + 4.84) \quad (19)$$

where:

H is the absolute pressure at the shaft centerline minus the cavity pressure, measured in feet of water.

With the above information in hand, the designer can verify the shape of the blade by determination of the propeller efficiency and the delivered power.

A. DESIGN ITERATIONS

In the previously discussed steps, it was assumed that the ideal thrust coefficient, C_{Ti}, was approximately seven percent higher than the thrust coefficient, Equation (9).

Once the initial design phase has been concluded, the drag to lift ratio, ε, can be determined and a more precise value of ideal thrust coefficient may be calculated. This may be used for additional iterations until a final value of thrust coefficient and power coefficient have been obtained. The ratio of thrust coefficient to the power coefficient determines the efficiency of the propeller.

A check of the adsorbed horsepower is made to see if the design meets the requirements of power available.

$$SHP_{(absorbed)} = C_p \times \rho \times D^2 \times V_a^2 \times S/(550 \times 8) \qquad (20)$$

B. STRENGTH OF THE BLADES

The final design step is the determination of the bending and torsional moments of the blades.

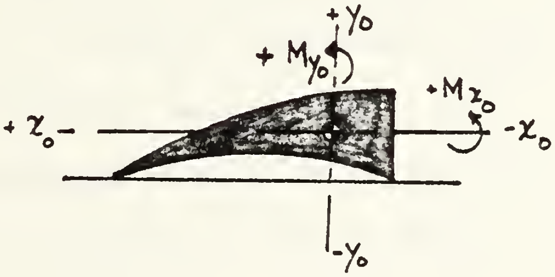


Figure 4. Bending and Torsional Moments

From the geometry of Figures 4 and 5 and from structural considerations,

$$M_{x0} \simeq M_{Tb} \cos \beta_i + M_{Qb} \sin \beta_i \tag{21}$$

$$M_{y0} \simeq M_{Tb} \sin \beta_i - M_{Qb} \cos \beta_i \tag{22}$$

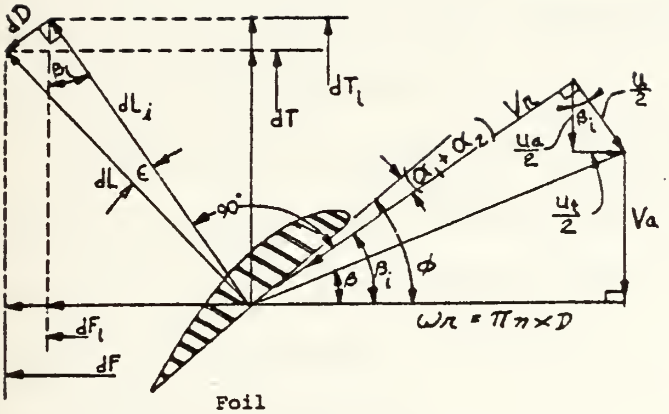
$$M_{Tb} = \frac{1}{2} \times \rho \times \pi \times R^3 \times V_a^2/z \int_{x_0}^{1} (x-x_0)(1-\varepsilon \tan \beta_i)\frac{dC_{Ti}}{dx}\, dx \tag{23}$$

$$M_{Qb} = \frac{1}{2} \times \rho \times \pi \times R^3 \times V_a^2/z \int_{x_0}^{1} (\tan \beta)(x-x_0) \times (1+\varepsilon/\tan \beta_i)\frac{dC_{Ti}}{dx}\, dx \tag{24}$$

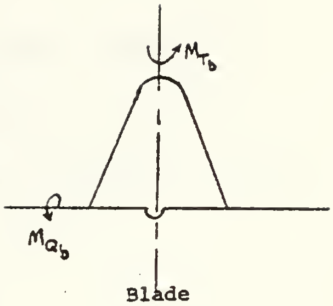
where x is the dimensionless station being analyzed.

It is to be noted from Figures 4 and 5, that M_{x0} and M_{y0} are approximate inasmuch as the precise expression is a function of ϕ rather than β_i. The difference between ϕ and β_i is α_F, where $\alpha_F = \alpha_1 + \alpha_2$, with a value of about 2. degrees. Except for heavily loaded blades, the use of β_i instead of ϕ is valid, since with heavy loads the angle of attack criticality increases.

The described design techniques have used thrust as a base. It is possible to use, instead, power as the base, i.e., C_p vice C_T.



Foil



Blade

β = ADVANCE ANGLE

β_i = HYDRODYNAMIC PITCH ANGLE

ϕ = FINAL PITCH ANGLE

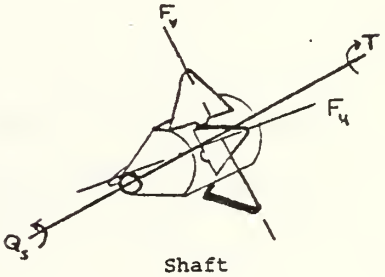
α_F = FINAL ANGLE OF ATTACK $(\alpha_1 + \alpha_2)$

α_1 = COMBINED ANGLE OF ATTACK THAT CONSIDERS THE IDEAL ANGLE OF ATTACK AND THE FRICTION CORRECTION *

α_2 = ANGLE OF ATTACK THAT CONSIDERS LIFTING SURFACE EFFECT

T = THRUST   D = DRAG   L = LIFT

F = TORQUE FORCE i = SUBSCRIPT FOR NON-VISCOUS



Shaft

* note α_1 in this sketch is $\alpha + \alpha_1$ as defined earlier.

Figure 5. Definition Sketch

III. COMPUTER AIDED DESIGN

A. INTRODUCTION

The basis of a Computer Aided Design (CAD) program is to make available to the designer the information that he needs for at least a first iteration. To be efficient, the CAD should have the following characteristics:

1. Be self-contained.

The entire program with all subroutines should be stored in a single data source, e.g., a computer disc, so that additional programs need not be loaded once the design process has commenced.

2. Be self-querying.

The variable inputs should be inserted in response to a computer question statement.

3. Be labor non-intensive.

Fixed parameters should be included in the program and not be required to be entered each time the program is exercised.

4. Be logical.

The computer program should follow a logical progression that is similar to the steps in a manual calculation, unless mathematical considerations dictate otherwise.

5. Be Segmented.

The program should contain logical breakpoints to facilitate future editing, including changes, deletions and/or insertions.

B. APPROXIMATIONS

The use of empirical data requires extensive curve fitting, interpolation and extrapolation. Frequently approximations may be made to the data that significantly reduces the calculation time. Such approximations are useful and valid only if they provide a high confidence level in the results. The following section details several of these approximations, together with numerical examples as a proof of confidence.

An expression of the optimum speed of advance, J_{opt}, was developed as,

$$J_{opt} = \frac{J_1 - (C_T^{0.5}/J \times J_1 - 0.56396 + 0.71765 \times \mathrm{Ln}(J_1))}{(C_T^{0.5}/J + 0.71765/J_1)} \qquad (25)$$

where:

$$J_1 = 1.206/(C_T^{0.5}/J + 0.63225)$$

This approximation provides a confidence level of 98%. The expected efficiency is extracted from the predicted performance charts extrapolated from 40 knots to 80 knots, for blades between ten and fourteen feet in diameter. This extraction was performed by Lagrangian curve fitting. To demonstrate the accuracy of these approximations, five runs were made at different values of RPM with the following conditions:

$V = 80$ kts $\quad R = 120{,}000$ lbs $\quad z = 6$

$SHP = 45{,}000$ Hp $\quad w = t = 0 \quad \rho = 2$ slug/ft^3

Submergence = 0.5

The results of these runs are shown in Table III where the subscript 'h' refers to manual calculations and the subscript 'c' refers to computer calculations. All calculations have been generated by this author.

TABLE III

SPEED OF ADVANCE/DIAMETER (MANUAL VS COMPUTER)

RUN	RPM	J_h	J_c	J_{opt_h}	J_{opt_c}	η_h	η_c	D_{opt_h}	D_{opt_c}
1	400	1.69	1.69	1.45	1.46	0.70	0.70	13.98	13.91
2	500	1.35	1.35	1.35	1.36	0.67	0.70	12.01	11.92
3	600	1.12	1.13	1.26	1.28	0.65	0.65	10.72	10.56
4	700	0.96	0.97	1.20	1.21	0.63	0.62	9.65	9.57
5	800	0.84	0.84	1.04	1.15	0.60	0.59	9.74	8.82

The determination of the uncorrected radial distribution of the blade's characteristics as well as the determination of the ideal thrust coefficient requires a knowledge of the ideal efficiency. In the manual mode, values were extracted from the curves of Kramer's Thrust coefficient. Once again, curve fitting techniques were employed. Because of the

shape of the empirical curves, the numerical approximation required five partitions.

The manual and computer values for the ideal efficiency are shown in Table IV for five runs at different values of η_i and C_{Ti} for z = 6.

TABLE IV

IDEAL EFFICIENCY (MANUAL VS COMPUTER)

Run	λ	C_{Ti}	η_{ih}	η_{ic}
1	0.500	0.0930	0.941	0.948
2	0.400	0.1260	0.930	0.949
3	0.400	0.1605	0.927	0.925
4	0.400	0.1954	0.905	0.901
5	0.400	0.2304	0.875	0.878

The camber correction coefficients, k_1 and k_2, must also be approximated, and are based on the ratio of expanded blade area to disk area, A_E/A_0. Table V shows a comparison of the values obtained from an empirical graph, subscript 'g' to the computer solution values, sucscript 'c'.

The graph used for this approximation, [1], has a maximum value of 1.2 for the ratio of the expanded blade area to disk area, A_E/A_0. Even with an extension of this value to nearly 1.6, the computed values of k_1 and k_2 appear to be well within reason.

TABLE V

CAMBER CORRECTION COEFFICIENTS (MANUAL VS COMPUTER)

A_E/A_0	K_{1g}	K_{1c}	K_{2g}	K_{2c}
1.54	*	1.06	*	2.31
0.75	1.03	1.00	2.10	2.13
0.72	1.06	1.06	2.10	2.09
0.33	1.01	1.00	1.70	1.67
0.25	1.02	1.00	1.65	1.67

*Point off empirical graph

Two additional curve fit solutions deal with the cavitation index and the lifting surface correction angles (α_1 and α_2). As indicated in Equation (16), the correction angles are a function of sigma and h. To indicate the degree of fit of the computer generated data for these approximations, Figures 6 and 7 show the computer plots with manually extracted data points from reference 6 superimposed.

The boldest modification in the development of this Computed Aided Design program was the complete removal of the Goldstein function and the induction factors from the calculations. This modification is required in order to simplify the design process. The Prandtl solution for irrotational motion of a screw surface in an inviscid, incompressible, continuous fluid lends itself to a simplified means of

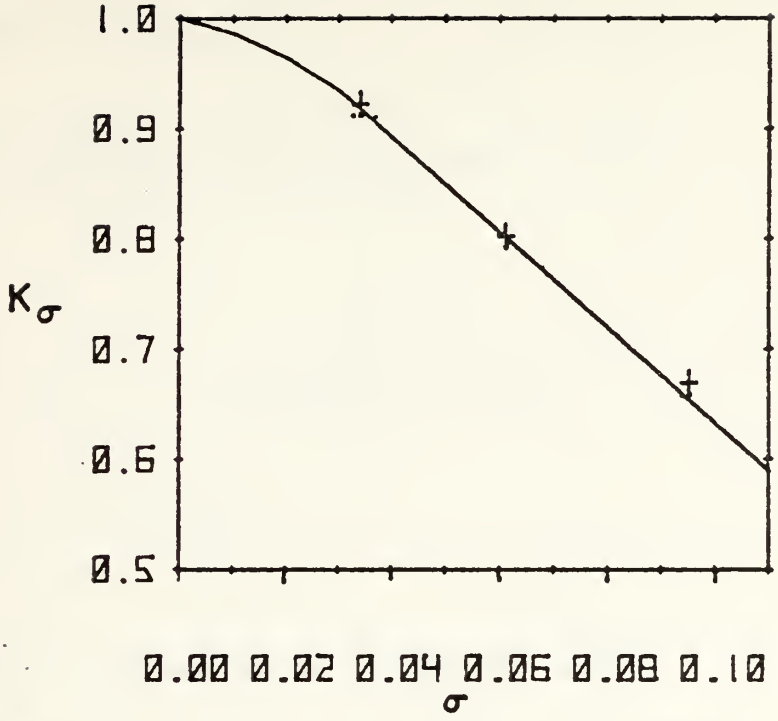


Figure 6. Cavitation Index (Manual vs Computer) [1]

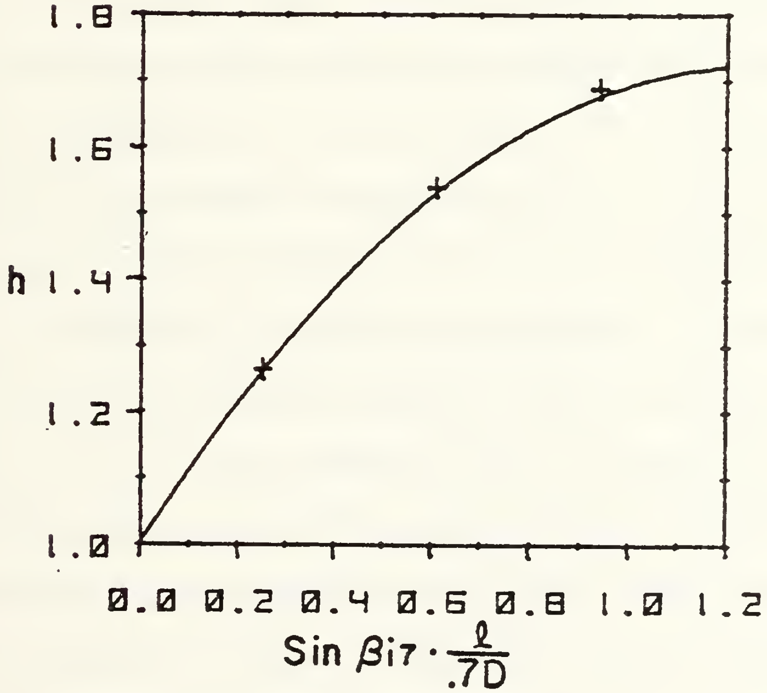


Figure 7. Lifting Surface Corrections (Manual vs Computer) [1]

determining the circulation and the lift coefficient. This approximate solution is,

$$\frac{z\,\Gamma\,N}{\pi\,u_a\,V_a} = \frac{z}{2\pi}\left(\frac{\mu^2}{1+\mu^2}\right)\cos^{-1} e^{-f} \qquad (26)$$

where:

$$f = (1 + \mu_0^2)^{1/2}(1 - \mu/\mu_0)$$

$$\mu = Nx/V_a$$

$$\mu_0 = N/V_a.$$

However, according to Goldstein [5],

> The accuracy of the (Prandtl) approximation increases with the number of blades and the ratio of the tip speed to the velocity of advance, but for given values of these numbers, we have found no means of estimating the error, since the exact solution has not been found.

Since Goldstein's work in 1929, NSRDC [2] has developed a more precise solution utilizing induction factors.

In the development of this program it was found that the direct use of the Prandtl approximation [5] as a substitute for the more complex Goldstein function produced excessive errors when compared to empirical results. It was therefore decided to use a modified solution which did not contain the term $(\mu^2/1 + \mu^2)$. This modified term, which is called the Wilson factor, Wf, provided a conservative solution with much less mathematical manipulation than was required if the Goldstein function of Lerb's induction factor method were used. The Wilson factor is defined as,

$$Wf = (z/2\pi) \times \cos^{-1} e^{-2f} \qquad (27)$$

Table VI shows a comparison of the Wilson factor, Wf, and the Goldstein function, κ, at several radial stations.

Table VI

WILSON FACTOR VS GOLDSTEIN FUNCTION

x	κ	Wf	κ/Wf
0.400	1.000	1.209	0.83
0.475	0.982	1.160	0.85
0.550	0.962	1.101	0.87
0.625	0.940	1.031	0.91
0.700	0.908	0.946	0.96
0.775	0.805	0.841	0.96
0.850	0.760	0.704	1.08
0.925	0.570	0.511	1.12

C. PROGRAM DESCRIPTION

1. Segment A

The first segment of the program, lines 10 through 630, is the input segment where the desired parameters are inserted in response to queries by the computer. These inputs, by line number, are shown in Table VII.

TABLE VII

COMPUTER PROGRAM INPUTS

Line	Input (units)
190	Ship maximum velocity (kts)
220	Ship maximum resistance (lbs)
250	Maximum available horsepower
280	Wake fraction (use zero if V = 60 kts)
310	Thrust deduction factor
340	Number of blades
370	Fraction of submergence of propeller
400	Assumed RPM
430	Fresh or salt water operation
450	Water temperature (Rankine)
540	Preliminary propeller diameter decision
610	Preliminary propeller diameter (ft)
630	Fluid density (slugs/ft^3)

2. Segment B

The second segment of the program, lines 640 through 930, computes and prints the basic parameters for the ensuing calculations. The printout, in the computer symbology, includes the thrust load coefficient, Ct, from existing formulae; the advance coefficient, J; the optimum advance coefficient, Jl; from numerical approximations; the optimum propeller diameter, Dl; the expected efficiency, E, also from numerical approximations; and the Shaft Horsepower, P.

3. Segment C

Because of the complexity and non-linearity of the empirical Kramer Thrust Coefficient curves, an extensive curve fitting process is required to cover the entire range. This is accomplished in a multi-step process from lines 940 through 3170. Lines 940 through 1370 are used to approximate the advance ratio, L, in order to enter the Kramer curves, and lines 1380 through 3170 determine the adjusted value, Ln, from the curves.

4. Segment D

Once the adjusted value Ln has been obtained, the ideal values of the parameters L_i, C_{ti} and E_i are determined in lines 3180 through 3300. All values, except E_i are from existing equations.

These values are then used in the first iteration for the ideal thrust coefficient, C_{ti}, in lines 3310 through 4460.

This segment is concluded with a printout of the delivered ideal thrust coefficient, C_{tide}, and the required ideal thrust coefficient, C_{ti}, for comparison purposes. Also printed at this point are the values of the tangent of the advance angle, tan B, the values of the Wilson factor, Wf, the circulation, G, and the distribution of the coefficient of lift times the chord-diameter ratio. All calculations, with the exception of the Wilson factor, are from existing equations.

5. Segment E

Lines 4050 through 4460, by the use of Simpson's Rule, calculate a first iteration of the ideal thrust coefficient, C_{tidl}, and a final iteration of the blade hydrodynamic delivered ideal thrust coefficient, C_{ti}, as well as the required C_{ti}.

6. Segment F

A second iteration of the ideal thrust coefficient is accomplished in lines 4470 through 5020 in order to verify the blade's hydrodynamic pitch angle. This is necessary inasmuch as the previous calculations were based on the original values of the ideal thrust coefficient vice the iterated values. The iteration continues until the delivered value is within 98% of the required value. All calculations are based on existing equations.

7. Segment G

Although the solution may be in hand by this point, it is of interest to recompute lambda based on the new parameter values and then to use this value as an alternate method in the design process. This is available in lines 5040 through 5390, but is currently by-passed in the program.

8. Segment H

The value of $C_L(\ell/D)$ is recalculated and ℓ_0 is printed out in lines 5400 through 5430 with the aid of a subroutine, and the shape of the blade is determined in lines 5440 through 5550, in addition to a first cut approximation of the EAR via existing formulae.

9. Segment I

The geometry of the foil, i.e., cross-sectional shape and all of the dimensions at each predetermined radial station, are calculated in lines 5560 through 6300. For each station there is a printout that specifies blade element thickness, height of curvature from the x-axis and blade width.

10. Segment J

The blade pitch is corrected for cavitation, friction and the lifting surface effects in lines 6310 through 6570. The printouts for this segment are similar to, but are of corrected values of, the data in the preceding segment, with the final pitch diameter ratio being determined.

11. Segment K

The segment from lines 6600 through 6850 determines the predicted propeller efficiency and manifests that the power demanded by the propeller does satisfy the available or required power.

12. Segment L

The bending and torsional moments along an arbitrary radial station are determined in the segment from lines 6860 through 7230 for various predetermined stations.

13. Segment M

The remainder of the program, through line 8450, is devoted to subroutines that perform the repetitive calculations required by the various segments and data.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This program is an approximate method for aiding in the design of supercavitating propeller blades. The numerical approximations complemented by the conversion factors and other constants result in a design that is about 90% accurate in the final sense as compared with information from reference 1. Inasmuch as this method uses essentially the same formulae and empirical curves as the 'manual' method, one could not hope for much better accuracy.

The principal advantage to this CAD program is that it reduces the conceptual design phase to minutes. It also provides a straightforward approach to the problem that can be: (a) easily followed, and (b) modified to fit the specific needs of the designer. The use of proven, computerized equations is much faster than table-look-ups and picking points off a graph. In addition, the repeatability of output is greatly enhanced.

The program will definitively demonstrate what combination of fundamental parameters will not yield a satisfactory design, e.g., negative coefficient of lift for a desired forward motion. This information provides the designer with great flexibility.

If the program does produce unsatisfactory solutions, the designer may vary the basic parameters. From the fluid

dynamics viewpoint the best parameter to change is RPM, inasmuch as RPM plays a major role in the design of propellers, and by adjusting the assumed RPM the resulting output is changed.

This program is equipped with an alternative design technique so that when the final tangent, β_i, at x = 0.7 is verified, a new ideal advance ratio may be calculated. This alternative is not a portion of the basic program but has been included for use if desired at a later time.

A comparison with a manually calculated theoretical design, as shown in Tables III, IV and V, demonstrates that this program is feasible and equally as accurate. However, the only definitive means of determining the validity of this program is to make a comparison with an experimental design.

This program can be used for all supercavitating propeller blades in an extremely wide range of speeds, submergences, thrusts and efficiencies.

B. RECOMMENDATIONS

A graphics routine would enhance the program and might even upgrade this program to a Computer Aided Engineering (CAE) and/or Computer Aided Manufacturing (CAM) status.

At present five- and seven-bladed propellers are excluded in this program, since it was too difficult to read the advance ratio off the Kramer Thrust Curve. This could be changed in the future.

The effect of the change of advance ratio on the final output has not been examined. The effect of this alternative

should be challenged in the future. In addition, the introduction of induction factors would be well worth the effort.

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4. Altmann, R.J. and Hecker, R., "High Performance Marine Propellers--An Overview", Marine Propulsion ASHE O.E.D., Vol. 2, pp. 23-95, 1976.

5. Goldstein, S. "On the Vortex Theory of Screw Propellers", Proceedings of the Royal Society of London, Series A, Vol. 63, 1929.

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APPENDIX A

HP-9845 COMPUTER PROGRAM

```
10   REM PROPELLER DESIGN THESIS CREATED BY MARC B. WILSON, LT., USCG
20   PRINTER IS 0
30   PRINT "The purpose of this program is to determine the following specificat
ions of a   supercavitating propeller:"
40   PRINT "Diameter (as a function of an assumed RPM)"
50   PRINT "Blade shape (chord dimensions at various radial stations)"
60   PRINT "Blade pitch and pitch distribution"
70   PRINT "Foil camber and thickness distribution"
80   PRINT "Blade bending moment at radial stations"
90   PRINT " "
100  PRINT "In order to give you the desired propeller please enter the known
           characteristics of the ship followed by pressing CONT."
110  PRINT " "
120  WAIT 1000
130  PRINTER IS 0
140  DISP "WOULD YOU LIKE A SYMBOLOGY LISTING (Y OR N)?";
150  INPUT C$
160  IF C$="Y" THEN GOSUB 8460
170  IF C$="N" THEN 180
180  DISP "Enter ship's maximum velocity in knots.";
190  INPUT V
200  PRINT "SHIP'S MAX SPEED IS";V
210  DISP "Enter ship's total resistance at maximum speed.";
220  INPUT Rt
230  PRINT "SHIP'S TOTAL RESISTANCE IS";Rt
240  DISP "Enter maximum available SHP.";
250  INPUT P
260  PRINT "SHIP'S MAX AVAILABLE SHP IS";P
270  DISP "Enter wake fraction at maximum speed.  Enter zero if 60 kts. or great
er.";
280  INPUT W
290  PRINT "THE WAKE FRACTION IS";W
300  DISP "Enter thrust deduction factor (see program explanation).";
```

```
310  INPUT Td
320  PRINT "THE THRUST DEDUCTION FACTOR IS";Td
330  DISP "Enter the number of blades on the propeller (2, 3, 4, 6, or 8).";
340  INPUT Z
350  PRINT "NUMBER OF BLADES ON PROPELLER IS";Z
360  DISP "Enter the fraction of submergence the propeller is to be at in the de
sign mode.";
370  INPUT S
380  PRINT "THE PERCENT OR FRACTION OF SUBMERGENCE EXPECTED OF THE CRAFT IS";S
390  DISP "Enter the assumed RPM of the propeller.";
400  INPUT N
410  PRINT "ASSUMED RPM IS";N
420  DISP "Do you desire fresh water or salt water calculations (FW or SW)?";
430  INPUT B$
440  DISP "Enter the assumed water temperature in Rankine (460+F).";
450  INPUT Temp
460  IF B$="FW" THEN New=6.53707233847E-3*EXP(-.01212214*Temp)
470  IF B$="SW" THEN New=7.22483376465E-3*EXP(-.012227212*Temp)
480  PRINT "CALCULATIONS ARE FOR ";B$
490  FIXED 3
500  PRINT "THE ASSUMED WATER TEMPERATURE IS";Temp,"                    VISCOSIT
Y (NU)=";New;"ft^2/sec"
510  PRINTER IS 16
520  PRINT PAGE
530  DISP "Do you need a preliminary propeller diameter (Y or N)?";
540  INPUT A$
550  IF A$="Y" THEN 570
560  IF A$="N" THEN 600
570  D=50*P^.2/N^.6
580  PRINT "Diameter =";D;"ft."
590  GOTO 620
600  DISP "Enter the expected propeller diameter in feet.";
610  INPUT D
```

```
620  DISP "Enter the fluid density (for salt water abt 2.0).";
630  INPUT Row
640  Va=V*(1-W)
650  T=Rt/(1-Td)
660  Ct=T/(Row/2*PI*(D^2/4)*(Va*1.689)^2*S)
670  FIXED 4
680  PRINTER IS 0
690  PRINT "The thrust-load coefficient =";Ct
700  Cts=Ct^.5
710  PRINT "The square root of the thrust-load coefficient is ";Cts
720  J=101.34*Va/(N*D)
730  PRINT "The advance coefficient, J =";J
740  J1=1.20265/(Cts/J+.63225)
750  FOR I=1 TO 6
760  J1=J1-(Cts/J*J1-.56396+.71765*LOG(J1))/(Cts/J+.71765/J1)
770  NEXT I
780  PRINT "The optimum advance coefficient is";J1
790  D1=101.34*Va/(N*J1)
800  PRINT "The optimum propeller diameter is";D1;"ft."
810  IF Va>=60 THEN 840
820  E=.55998-.0269034*D1+.00982141*D1^2-.000416665*D1^3
830  GOTO 850
840  E=2.105567-.498693*D1+.0517855*D1^2-.00166667*D1^3
850  PRINT "The expected efficiency is";E
860  P1=T*Va*1.689/(E*550)
870  PRINT "The SHP for this optimum propeller is";P1
880  L=101.34*Va/(PI*N*D1)
890  Cto=T/(Row/2*PI*(D1^2/4)*(Va*1.689)^2*S)
900  Cti=1.07*Cto
910  Mouc=N/60*.40/(Va*1.689)
920  Mouo=N/60/(Va*1.689)
```

```
930  Wfo=Z/(2*PI)*ACS(EXP(-2*(1+Mouo^2)^.5*(1-Mouc/Mouo)))
940  IF L>9.5 THEN L=10
950  IF (L<=9.5) AND (L>8.5) THEN L=9.0
960  IF (L<=8.5) AND (L>7.5) THEN L=8
970  IF (L<=7.5) AND (L>6.5) THEN L=7.0
980  IF (L<=6.5) AND (L>5.5) THEN L=6
990  IF (L<=5.5) AND (L>4.5) THEN L=5.0
1000 IF (L<=4.5) AND (L>3.5) THEN L=4
1010 IF (L<=3.5) AND (L>=3) THEN L=3
1020 IF (L<3) AND (L>=2.5) THEN L=2.5
1030 IF (L<2.5) AND (L>=2) THEN L=2
1040 IF (L<2) AND (L>=1.5) THEN L=1.5
1050 IF (L<1.5) AND (L>=.95) THEN L=1
1060 IF (L<.95) AND (L>=.85) THEN L=.9
1070 IF (L<.85) AND (L>=.75) THEN L=.8
1080 IF (L<.75) AND (L>=.65) THEN L=.70
1090 IF (L<.65) AND (L>=.55) THEN L=.6
1100 IF (L<.55) AND (L>=.45) THEN L=.5
1110 IF (L<.45) AND (L>=.35) THEN L=.40
1120 IF (L<.35) AND (L>=.3) THEN L=.3
1130 IF (L<.3) AND (L>=.25) THEN L=.25
1140 IF (L<.25) AND (L>.15) THEN L=.2
1150 IF (L<=.15) AND (L>.10) THEN L=.15
1160 IF (L<=.10) AND (L>=.095) THEN L=.10
1170 IF (L<.095) AND (L>=.085) THEN L=.09
1180 IF (L<.085) AND (L>=.075) THEN L=.08
1190 IF (L<.075) AND (L>=.065) THEN L=.07
1200 IF (L<.065) AND (L>=.055) THEN L=.06
1210 IF (L<.055) AND (L>=.045) THEN L=.05
1220 IF (L<.045) AND (L>=.035) THEN L=.04
1230 IF (L<.035) AND (L>=.03) THEN L=.03
```

```
1240 IF (L<.03) AND (L>=.025) THEN L=.025
1250 IF (L<.025) AND (L>.015) THEN L=.020
1260 IF (L<=.015) AND (L>.010) THEN L=.015
1270 IF (L<=.010) AND (L>=.0095) THEN L=.010
1280 IF (L<.0095) AND (L>=.00850) THEN L=.009
1290 IF (L<.00850) AND (L>=.0075) THEN L=.008
1300 IF (L<.0075) AND (L>=.00650) THEN L=.007
1310 IF (L<.00650) AND (L>=.0055) THEN L=.006
1320 IF (L<.0055) AND (L>=.00450) THEN L=.005
1330 IF (L<.00450) AND (L>=.0035) THEN L=.004
1340 IF (L<.0035) AND (L>=.003) THEN L=.003
1350 IF (L<.003) AND (L>=.0025) THEN L=.0025
1360 IF (L<.0025) AND (L>.0015) THEN L=.002
1370 IF (L<=.0015) AND (L>.001) THEN L=.0015
1380 IF Z=2 THEN L=Ln
1390 IF (L=.0015) AND (Z=3) THEN Ln=.00125
1400 IF (L=.0015) AND (Z=4) THEN Ln=.00110
1410 IF (L=.002) AND (Z=3) THEN Ln=.00165
1420 IF (L=.002) AND (Z=4) THEN Ln=.00145
1430 IF (L=.002) AND (Z=6) THEN Ln=.00130
1440 IF (L=.002) AND (Z=8) THEN Ln=.0012
1450 IF (L=.0025) AND (Z=3) THEN Ln=.002
1460 IF (L=.0025) AND (Z=4) THEN Ln=.00175
1470 IF (L=.0025) AND (Z=6) THEN Ln=.00155
1480 IF (L=.0025) AND (Z=8) THEN Ln=.00145
1490 IF (L=.003) AND (Z=3) THEN Ln=.00245
1500 IF (L=.003) AND (Z=4) THEN Ln=.00220
1510 IF (L=.003) AND (Z=6) THEN Ln=.00185
1520 IF (L=.003) AND (Z=8) THEN Ln=.001700
1530 IF (L=.004) AND (Z=3) THEN Ln=.00320
1540 IF (L=.004) AND (Z=4) THEN Ln=.00285
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```
1550 IF (L=.004) AND (Z=6) THEN Ln=.0025
1560 IF (L=.004) AND (Z=8) THEN Ln=.00225
1570 IF (L=.005) AND (Z=3) THEN Ln=.004
1580 IF (L=.005) AND (Z=4) THEN Ln=.00355
1590 IF (L=.005) AND (Z=6) THEN Ln=.003
1600 IF (L=.005) AND (Z=8) THEN Ln=.00275
1610 IF (L=.006) AND (Z=3) THEN Ln=.00395
1620 IF (L=.006) AND (Z=4) THEN Ln=.00425
1630 IF (L=.006) AND (Z=6) THEN Ln=.00375
1640 IF (L=.006) AND (Z=8) THEN Ln=.00335
1650 IF (L=.007) AND (Z=3) THEN Ln=.00585
1660 IF (L=.007) AND (Z=4) THEN Ln=.005
1670 IF (L=.007) AND (Z=6) THEN Ln=.00435
1680 IF (L=.007) AND (Z=8) THEN Ln=.00395
1690 IF (L=.008) AND (Z=3) THEN Ln=.00655
1700 IF (L=.008) AND (Z=4) THEN Ln=.00585
1710 IF (L=.008) AND (Z=6) THEN Ln=.005
1720 IF (L=.008) AND (Z=8) THEN Ln=.00450
1730 IF (L=.009) AND (Z=3) THEN Ln=.00725
1740 IF (L=.009) AND (Z=4) THEN Ln=.00650
1750 IF (L=.009) AND (Z=6) THEN Ln=.00575
1760 IF (L=.009) AND (Z=8) THEN Ln=.005
1770 IF (L=.010) AND (Z=3) THEN Ln=.00815
1780 IF (L=.010) AND (Z=4) THEN Ln=.00725
1790 IF (L=.010) AND (Z=6) THEN Ln=.00650
1800 IF (L=.010) AND (Z=8) THEN Ln=.00595
1810 IF (L=.015) AND (Z=3) THEN Ln=.0125
1820 IF (L=.015) AND (Z=4) THEN Ln=.01150
1830 IF (L=.015) AND (Z=6) THEN Ln=.0095
1840 IF (L=.015) AND (Z=8) THEN Ln=.00850
1850 IF (L=.020) AND (Z=3) THEN Ln=.017
```

```
1860 IF (L=.020) AND (Z=4) THEN Ln=.0145
1870 IF (L=.020) AND (Z=6) THEN Ln=.013
1880 IF (L=.020) AND (Z=8) THEN Ln=.0120
1890 IF (L=.025) AND (Z=3) THEN Ln=.0205
1900 IF (L=.025) AND (Z=4) THEN Ln=.018
1910 IF (L=.025) AND (Z=6) THEN Ln=.0155
1920 IF (L=.025) AND (Z=8) THEN Ln=.0145
1930 IF (L=.03) AND (Z=3) THEN Ln=.025
1940 IF (L=.03) AND (Z=4) THEN Ln=.022
1950 IF (L=.03) AND (Z=6) THEN Ln=.018
1960 IF (L=.03) AND (Z=8) THEN Ln=.017
1970 IF (L=.04) AND (Z=3) THEN Ln=.033
1980 IF (L=.04) AND (Z=4) THEN Ln=.028
1990 IF (L=.04) AND (Z=6) THEN Ln=.025
2000 IF (L=.04) AND (Z=8) THEN Ln=.023
2010 IF (L=.05) AND (Z=3) THEN Ln=.041
2020 IF (L=.05) AND (Z=4) THEN Ln=.036
2030 IF (L=.05) AND (Z=5) THEN Ln=.031
2040 IF (L=.05) AND (Z=8) THEN Ln=.028
2050 IF (L=.06) AND (Z=3) THEN Ln=.049
2060 IF (L=.06) AND (Z=4) THEN Ln=.043
2070 IF (L=.06) AND (Z=6) THEN Ln=.038
2080 IF (L=.06) AND (Z=8) THEN Ln=.034
2090 IF (L=.07) AND (Z=3) THEN Ln=.0585
2100 IF (L=.07) AND (Z=4) THEN Ln=.0515
2110 IF (L=.07) AND (Z=6) THEN Ln=.045
2120 IF (L=.07) AND (Z=8) THEN Ln=.0405
2130 IF (L=.08) AND (Z=3) THEN Ln=.0655
2140 IF (L=.08) AND (Z=4) THEN Ln=.059
2150 IF (L=.08) AND (Z=6) THEN Ln=.051
2160 IF (L=.08) AND (Z=8) THEN Ln=.0465
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2170 IF (L=.09) AND (Z=3) THEN Ln=.073
2180 IF (L=.09) AND (Z=4) THEN Ln=.0655
2190 IF (L=.09) AND (Z=6) THEN Ln=.058
2200 IF (L=.09) AND (Z=8) THEN Ln=.0515
2210 IF (L=.10) AND (Z=3) THEN Ln=.081
2220 IF (L=.10) AND (Z=4) THEN Ln=.072
2230 IF (L=.10) AND (Z=6) THEN Ln=.062
2240 IF (L=.10) AND (Z=8) THEN Ln=.058
2250 IF (L=.15) AND (Z=3) THEN Ln=.125
2260 IF (L=.15) AND (Z=4) THEN Ln=.115
2270 IF (L=.15) AND (Z=6) THEN Ln=.095
2280 IF (L=.15) AND (Z=8) THEN Ln=.087
2290 IF (L=.2) AND (Z=3) THEN Ln=.165
2300 IF (L=.2) AND (Z=4) THEN Ln=.145
2310 IF (L=.2) AND (Z=6) THEN Ln=.130
2320 IF (L=.2) AND (Z=8) THEN Ln=.120
2330 IF (L=.25) AND (Z=3) THEN Ln=.210
2340 IF (L=.25) AND (Z=4) THEN Ln=.180
2350 IF (L=.25) AND (Z=6) THEN Ln=.165
2360 IF (L=.25) AND (Z=8) THEN Ln=.14
2370 IF (L=.3) AND (Z=3) THEN Ln=.25
2380 IF (L=.3) AND (Z=4) THEN Ln=.225
2390 IF (L=.3) AND (Z=6) THEN Ln=.195
2400 IF (L=.3) AND (Z=8) THEN Ln=.180
2410 IF (L=.40) AND (Z=3) THEN Ln=.33
2420 IF (L=.40) AND (Z=4) THEN Ln=.3
2430 IF (L=.40) AND (Z=6) THEN Ln=.26
2440 IF (L=.40) AND (Z=8) THEN Ln=.24
2450 IF (L=.5) AND (Z=3) THEN Ln=.42
2460 IF (L=.5) AND (Z=4) THEN Ln=.38
2470 IF (L=.5) AND (Z=6) THEN Ln=.33
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2480 IF (L=.5) AND (Z=8) THEN Ln=.3
2490 IF (L=.6) AND (Z=3) THEN Ln=.5
2500 IF (L=.6) AND (Z=4) THEN Ln=.46
2510 IF (L=.6) AND (Z=6) THEN Ln=.40
2520 IF (L=.6) AND (Z=8) THEN Ln=.370
2530 IF (L=.70) AND (Z=3) THEN Ln=.59
2540 IF (L=.70) AND (Z=4) THEN Ln=.53
2550 IF (L=.70) AND (Z=6) THEN Ln=.48
2560 IF (L=.70) AND (Z=8) THEN Ln=.45
2570 IF (L=.8) AND (Z=3) THEN Ln=.68
2580 IF (L=.8) AND (Z=4) THEN Ln=.6
2590 IF (L=.8) AND (Z=6) THEN Ln=.555
2600 IF (L=.8) AND (Z=8) THEN Ln=.495
2610 IF (L=.9) AND (Z=3) THEN Ln=.77
2620 IF (L=.9) AND (Z=4) THEN Ln=.690
2630 IF (L=.9) AND (Z=6) THEN Ln=.610
2640 IF (L=.9) AND (Z=8) THEN Ln=.57
2650 IF (L=1) AND (Z=3) THEN Ln=.85
2660 IF (L=1) AND (Z=4) THEN Ln=.78
2670 IF (L=1) AND (Z=6) THEN Ln=.695
2680 IF (L=1) AND (Z=8) THEN Ln=.64
2690 IF (L=1.5) AND (Z=3) THEN Ln=1.3
2700 IF (L=1.5) AND (Z=4) THEN Ln=1.2
2710 IF (L=1.5) AND (Z=6) THEN Ln=1.05
2720 IF (L=1.5) AND (Z=8) THEN Ln=.97
2730 IF (L=2) AND (Z=3) THEN Ln=1.7
2740 IF (L=2) AND (Z=4) THEN Ln=1.55
2750 IF (L=2) AND (Z=6) THEN Ln=1.35
2760 IF (L=2) AND (Z=8) THEN Ln=1.3
2770 IF (L=2.5) AND (Z=3) THEN Ln=2.05
2780 IF (L=2.5) AND (Z=4) THEN Ln=1.85
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2790 IF (L=2.5) AND (Z=6) THEN Ln=1.7
2800 IF (L=2.5) AND (Z=8) THEN Ln=1.6
2810 IF (L=3) AND (Z=3) THEN Ln=2.55
2820 IF (L=3) AND (Z=4) THEN Ln=2.4
2830 IF (L=3) AND (Z=6) THEN Ln=2.15
2840 IF (L=3) AND (Z=8) THEN Ln=1.9
2850 IF (L=4) AND (Z=3) THEN Ln=3.4
2860 IF (L=4) AND (Z=4) THEN Ln=3.15
2870 IF (L=4) AND (Z=6) THEN Ln=2.8
2880 IF (L=4) AND (Z=8) THEN Ln=2.6
2890 IF (L=5.0) AND (Z=3) THEN Ln=4.2
2900 IF (L=5.0) AND (Z=4) THEN Ln=3.9
2910 IF (L=5.0) AND (Z=6) THEN Ln=3.5
2920 IF (L=5.0) AND (Z=8) THEN Ln=3.2
2930 IF (L=6) AND (Z=3) THEN Ln=5.1
2940 IF (L=6) AND (Z=4) THEN Ln=4.7
2950 IF (L=6) AND (Z=6) THEN Ln=4.15
2960 IF (L=6) AND (Z=8) THEN Ln=3.85
2970 IF (L=7.0) AND (Z=3) THEN Ln=6
2980 IF (L=7.0) AND (Z=4) THEN Ln=5.5
2990 IF (L=7.0) AND (Z=6) THEN Ln=4.9
3000 IF (L=7.0) AND (Z=8) THEN Ln=4.5
3010 IF (L=8) AND (Z=3) THEN Ln=6.85
3020 IF (L=8) AND (Z=4) THEN Ln=6.1
3030 IF (L=8) AND (Z=6) THEN Ln=5.5
3040 IF (L=8) AND (Z=8) THEN Ln=5.0
3050 IF (L=9.0) AND (Z=3) THEN Ln=7.85
3060 IF (L=9.0) AND (Z=4) THEN Ln=7.0
3070 IF (L=9.0) AND (Z=6) THEN Ln=6.3
3080 IF (L=9.0) AND (Z=8) THEN Ln=5.9
3090 IF (L=10) AND (Z=3) THEN Ln=8.5
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```
3100 IF (L=10) AND (Z=4) THEN Ln=7.8
3110 IF (L=10) AND (Z=6) THEN Ln=7.0
3120 IF (L=10) AND (Z=8) THEN Ln=6.5
3130 IF Ln<.05 THEN 3210
3140 IF (Ln>=.05) AND (Ln<.2) THEN Ei=.03449117777*Cti^2-.2613653861*Cti+.993614
07312
3150 IF (Ln>=.2) AND (Ln<.32) THEN 3240
3160 IF (Ln>=.32) AND (Ln<.70) THEN Ei=-1.1461914*Cti^2-.7755191745*Cti+.9947020
5707
3170 FIXED 3
3180 Ei=-.0068551019*(.23752192772 4*EXP(-.849883844879*Ln))^3+.0666894512*(.2375
21927724*EXP(-.849883844879*Ln))^2
3190 Ei=Ei-.2813532442*(.237521927724*EXP(-.849883844879*Ln))+.99664570079
3200 GOTO 3260
3210 FIXED 3
3220 Ei=-.00224972445*Cti^3+.0347185502*Cti^2-.20642857*Cti+.9927469921
3230 GOTO 3260
3240 FIXED 3
3250 Ei=1.04197226869*EXP(-.744201784811*Cti)
3260 PRINT "L =";L,"Cti=";Cti,"Ln =";Ln
3270 PRINT "The ideal efficiency (Ei) is ";Ei
3280 Eps7=0
3290 Li=L/Ei
3300 PRINT "Li=";Li
3310 IF Eps7>0 THEN PRINT "THE FOLLOWING IS RECALCULATED USING EPSILON!"
3320 IF Eps7>0 THEN Cti=Cto/(1-2*Eps7*Li)
3330 Sum1=0
3340 Sum72=0
3350 Sum83=0
3360 Sum85=0
3370 Sumf=0
3380 Sum2=0
3390 Sprod=0
3400 PRINT SPA(4);"X";SPA(6);"TAN Bi";SPA(5.0);"COS Bi";SPA(6);"WF";SPA(8);"G";S
PA(8),"C 1/D"
```

```
3410 FOR X=.40 TO .925 STEP .075
3420 Tbi=Li/.70
3430 Tb=101.34*Va/(PI*N*D1*X)
3440 B=ATN(Tb)
3450 Sb=SIN(B)
3460 IF X=.40 THEN Pdr=.984
3470 IF X=.475 THEN Pdr=.9886
3480 IF X=.55 THEN Pdr=.9926
3490 IF X=.625 THEN Pdr=.9962
3500 IF X=.70 THEN Pdr=1
3510 IF X=.775 THEN Pdr=1.0044
3520 IF X=.85 THEN Pdr=1.009
3530 IF X=.925 THEN Pdr=1.0114
3540 Pdix=PI*X*Tbi
3550 Pitch=D1*Pdix
3560 Tbix=Li/X
3570 Bix=ATN(Tbix)
3580 Cbix=COS(Bix)
3590 Sbix=SIN(Bix)
3600 Bixb=Bix-B
3610 Sbixb=SIN(Bixb)
3620 S3=Sbix*Sbixb/Sb
3630 X1=1/Tb
3640 Xa=X1-S3
3650 Invli=PI*D1/(X*Pitch)
3660 A=1/Ei-1
3670 Ap=(1+A)*Tb*PI*D1/Pitch
3680 Ut=2*Ap*N*.1047*D1*X/2
3690 Ua=A*Va*2*1.689
3700 REM Wf1=EXP(1)*((1+(Ua*X*60/N)^2)/(Ua*X*60/N)^2)
3710 REM Wf=Wf1*Z*PI*D1*N/(60*2*PI*Va*1.689*Ua)
```

```
3720 Mou=N/60*X/(Va*1.689)
3730 Mouo=N/60/(Va*1.689)
3740 REM Mou1=Ua*X/(N/60)
3750 REM Mouo1=Ua/(N/60)
3760 REM Wf1=Z/(2*PI)*ACS(EXP(-2*(1+Mouo1^2)^.5*(1-Mou1/Mouo1)))
3770 Wf=Z/(2*PI)*ACS(EXP(-2*(1+Mouo^2)^.5*(1-Mou/Mouo)))
3780 Vor=X*Wf*S3
3790 G=2*X*Wf/Z*(1/Ei-1)*(TAN(Bix)/(TAN(Bix)^2+1))
3800 Clld=2*PI*Cbix*G/Xs
3810 Ctdi=8*Vor*Xs
3820 IF X=.40 THEN Simp=1
3830 IF X=.475 THEN Simp=4
3840 IF X=.55 THEN Simp=2
3850 IF X=.625 THEN Simp=4
3860 IF X=.70 THEN Simp=2
3870 IF X=.775 THEN Simp=4
3880 IF X=.85 THEN Simp=2
3890 IF X=.925 THEN Simp=4
3900 IF X=1 THEN Simp=1
3910 Prod=Ctdi*Simp
3920 Sprod=Prod+Sprod
3930 FIXED 4
3940 PRINT USING "M.DDDD,4X,D.DDDD,5X,D.DDDD,4X,D.DDDD,4X,D.DDDD,5X,D.DDDD";X,Tb
ix,Cbix,Wf,G,Clld
3950 REM PRINT "X =";X;"Tb =";Tb;"B =";B;"Sb =";Sb;"Tbi =";Tbi;"Bi =";Bi;"Sbi ="
;Sbi
3960 REM PRINT "X =";X;"BIB =";Bib;"SBIB =";Sbib;"S3 =";S3;"X/L =";Xl;"XS =";Xs,
"1/Li =";Invli;"Wf=";Wf;"SUM =";Sprod
3970 NEXT X
3980 FIXED 3
3990 PRINT "THE SUM OF THE PRODUCTS IS";Sprod
4000 Ctide=.075*Sprod/3
4010 PRINT "THE DELIVERED Cti =";Ctide,"THE REQUIRED Cti =";Cti
4020 REM PRINT SPA(4);"X";SPA(10);"THE NEW TAN Bi";SPA(4);"WILSON FACTOR";SPA(8)
;"dCti * Simpson"
```

```
4030 FLOAT 3
4040 FOR X=.40 TO .925 STEP .075
4050 Tbi=Li/X
4060 Tbic=Tbi*(1+(Cti-Ctide)/(5.0*Cti))
4070 Bic=ATN(Tbic)
4080 Sbic=SIN(Bic)
4090 Tb=101.34*Va/(PI*N*D1*X)
4100 B=ATN(Tb)
4110 Bicb=Bic-B
4120 Sbicb=SIN(Bicb)
4130 S3c=Sbic*Sbicb/Sb
4140 X1=1/Tb
4150 Xsc=X1-S3c
4160 Liinv=1/X*Tbic
4170 Mou=N/60*X/(Va*1.689)
4180 Mouo=N/60/(Va*1.689)
4190 Wf=Z/(2*PI)*ACS(EXP(-2*(1+Mouo^2)^.5*(1-Mou/Mouo)))
4200 Vorc=X*Wf*S3c
4210 Ctdic=8*Vorc*Xsc
4220 IF X=.40 THEN Simp=1
4230 IF X=.475 THEN Simp=4
4240 IF X=.55 THEN Simp=2
4250 IF X=.625 THEN Simp=4
4260 IF X=.70 THEN Simp=2
4270 IF X=.775 THEN Simp=4
4280 IF X=.85 THEN Simp=2
4290 IF X=.925 THEN Simp=4
4300 IF X=1 THEN Simp=1
4310 Prodc=Ctdic*Simp
4320 Sum1=Prodc+Sum1
4330 REM PRINT X;SPA(7.0);Tbic;SPA(12.0);Wf;SPA(12.0),Prodc
```

```
4340 NEXT X
4350 FIXED 4
4360 REM PRINT "THE SUM OF THE CORRECTED PRODUCTS IS";Sum1
4370 Ctid1=.075*Sum1/3
4380 PRINT "THE VERIFYING DELIVERED Cti =";Ctid1,"THE REQUIRED Cti =";Cti
4390 Tbi=Li/.70
4400 Tbic=Tbi*(1+(Cti-Ctide)/(5.0*Cti))
4410 I=Tbic-Ctid1*((Tbic-Tbi)/(Ctid1-Ctide))
4420 Tbif=Cti*((Tbic-Tbi)/(Ctid1-Ctide))+I
4430 REM PRINT "THE FINAL TANGENT Bi IS";Tbif
4440 REM DEG
4450 Bif=ATN(Tbif)
4460 REM PRINT "THE FINAL Bi =";Bif
4470 Pit=.70*D1*Tbif*PI
4480 Pd=Pit/D1
4490 FOR X=.40 TO .925 STEP .075
4500 IF X=.40 THEN Pdr=.984
4510 IF X=.475 THEN Pdr=.9886
4520 IF X=.55 THEN Pdr=.9926
4530 IF X=.625 THEN Pdr=.9962
4540 IF X=.70 THEN Pdr=1
4550 IF X=.775 THEN Pdr=1.0044
4560 IF X=.85 THEN Pdr=1.009
4570 IF X=.925 THEN Pdr=1.0114
4580 Pdix1=Pd*Pdr
4590 Pit1=D1*Pdix1
4600 Tbi1=Pit1/(PI*D1*X)
4610 Bi1=ATN(Tbi1)
4620 Sbi1=SIN(Bi1)
4630 Tb=101.34*Va/(PI*N*D1*X)
4640 B=ATN(Tb)
```

```
4650 Sb=SIN(B)
4660 Bi1b=Bi1-B
4670 Sbi1b=SIN(Bi1b)
4680 Ut2va=Sbi1*Sbi1b/Sb
4690 Xl=1/Tb
4700 Xlut2va=Xl-Ut2va
4710 Invli1=1/(X*Tbi1)
4720 Mou=N/60*X/(Va*1.689)
4730 Mouo=N/60/(Va*1.689)
4740 Wf=Z/(2*PI)*ACS(EXP(-2*(1+Mouo^2)^.5*(1-Mou/Mouo)))
4750 Xwut2va=X*Wf*Ut2va
4760 Dcti1=8*Xwut2va*Xlut2va
4770 IF X=.40 THEN Simp=1
4780 IF X=.475 THEN Simp=4
4790 IF X=.55 THEN Simp=2
4800 IF X=.625 THEN Simp=4
4810 IF X=.70 THEN Simp=2
4820 IF X=.775 THEN Simp=4
4830 IF X=.85 THEN Simp=2
4840 IF X=.925 THEN Simp=4
4850 Prod1=Dcti1*Simp
4860 Sum2=Prod1+Sum2
4870 REM PRINT X;Tbi1;Xlut2va;Invli1;Wf;Dcti1;Prod1
4880 NEXT X
4890 Ctid2=.075*Sum2/3
4900 Percent=Cti*.99
4910 IF Ctid2<Percent THEN Ctid2=Ctide
4920 Incr=Cti*2
4930 IF Ctid2>Incr THEN GOSUB 8740
4940 IF (Ctid2<Incr) AND (Ctid2>Percent) THEN 4960
4950 IF Ctid2=Ctide THEN 4040
```

```
4960 PRINT "THE FINAL TANGENT OF BETA SUB i IS";Tbif
4970 DEG
4980 Bif=ATN(Tbif)
4990 PRINT "THAT ANGLE IN DEGREES AT 0.7R IS";Bif
5000 RAD
5010 Bif=ATN(Tbif)
5020 PRINT "THE FINAL BETAi HAS BEEN VERIFIED.  YOU MAY PROCEED WITH A CONFIDENC
E FACTOR OF 98%."
5030 IF Eps7>0 THEN GOTO 6820
5040 Pit2=.70*D1*Tbif*PI
5050 Pd2=Pit2/D1
5060 Li2=.70*Tbif
5070 REM    PRINT SPA(3);"X";SPA(4);"COSBi";SPA(2);"CIRC";SPA(3);"C 1/D"
5080 FOR X=.40 TO .925 STEP .075
5090 IF X=.40 THEN Pdr=.984
5100 IF X=.475 THEN Pdr=.9886
5110 IF X=.55 THEN Pdr=.9926
5120 IF X=.625 THEN Pdr=.9962
5130 IF X=.70 THEN Pdr=1
5140 IF X=.775 THEN Pdr=1.0044
5150 IF X=.85 THEN Pdr=1.009
5160 IF X=.925 THEN Pdr=1.0114
5170 Pdix2=Pd2*Pdr
5180 Pit3=D1*Pdix2
5190 REM Tbi2=Li2/X    This is an alternate approach using a new Lil
5200 Tbi2=Li/X
5210 Bi2=ATN(Tbi2)
5220 Cbi2=COS(Bi2)
5230 Sbi2=SIN(Bi2)
5240 Tb=101.34*Va/(PI*N*D1*X)
5250 B=ATN(Tb)
5260 Sb=SIN(B)
```

```
5270 Sbi2b=SIN(Bi2-B)
5280 Ten=Sbi2*Sbi2b/Sb
5290 Eleven=1/Tb
5300 Twelve=Eleven-Ten
5310 Mou=N/60*X/(Va*1.689)
5320 Mouo=N/60/(Va*1.639)
5330 Wf=Z/(2*PI)*ACS(EXP(-2*(1+Mouo^2)^.5*(1-Mou/Mouo)))
5340 Fifteen=X*Wf*Ten
5350 Fpcbz=4*PI*Cbi2/Z
5360 Circ=2*X*Wf/Z*(1/Ei-1)*(Tbi2/(Tbi2^2+1))
5370 Clld1=2*PI*Circ*Cbi2/Twelve
5380 REM    PRINT X;Cbi2;Circ;Clld1
5390 NEXT X
5400 X=.70
5410 GOSUB 7460
5420 Lo=Clld*D1/.16
5430 PRINT "Lo=";Lo
5440 Eear=Lo/D1*Z/2.1
5450 PRINT " "
5460 PRINT "THE APPROXIMATE (WITHIN 30%) EXPANDED AREA RATIO (EAR) IS ";Eear
5470 PRINT " "
5480 Cl=Clld*D1/Lo
5490 Cl7=Cl
5500 GOSUB 7430
5510 A7=Alpha
5520 A7=2
5530 Ylmax7=.015608
5540 Ymax7=Ylmax7*Lo
5550 PRINT SPA(3);"X";SPA(4);"1/10.7";SPA(2);" lx ";SPA(4);"Cl";SPA(4);"ALPHA";S
PA(3);"y/lmax";SPA(2);"ymax"
5560 FOR X=.40 TO .925 STEP .075
5570 GOSUB 7460
```

```
5580 IF X=.40 THEN L17=1.088
5590 IF X=.475 THEN L17=1.086
5600 IF X=.55 THEN L17=1.073
5610 IF X=.625 THEN L17=1.046
5620 IF X=.70 THEN L17=1
5630 IF X=.775 THEN L17=.903
5640 IF X=.85 THEN L17=.763
5650 IF X=.925 THEN L17=.565
5660 Lx=Lo*L17
5670 Cl=Clld*D1/Lx
5680 IF (Cl>=0) AND (Cl<.0548) THEN Alpha=36.5*Cl
5690 IF (Cl>=.0548) AND (Cl<.2) THEN Alpha=2
5700 IF Cl>=.2 THEN Alpha=10*Cl
5710 Ylmax=.1553*Cl-.00462*Alpha
5720 Ymax=Ylmax*Lx
5730 PRINT USING "M.DDD,2X,D.DDDD,2X.D.DDDD,2X,.DDDD,2X,D.DDDD,2X,.DDDD,2X,.DDDD
";X,L17,Lx,Cl,Alpha,Ylmax,Ymax
5740 NEXT X
5750 PRINT " "
5760 PRINT SPA(2);"d/l";SPA(4);"y";SPA(6);"t/l";SPA(4);"t(ft)"
5770 DIM A(14)
5780 DATA .0075,.0125,.05,.1,.2,.3,.4,.5,.6,.7,.8,.9,.95,1.0
5790 FOR I=1 TO 14
5800 READ Dlr
5810 GOSUB 7870
5820 Y=Ymax7*Yymr
5830 Tlr=Fp*.16+Np*A7
5840 Tft=Tlr*Lo
5850 PRINT USING "MD.DDDD,2X,.DDDD,2X,.DDDD,2X,.DDDD";Dlr,Y,Tlr,Tft
5860 NEXT I
5870 RESTORE 5780
5880 FOR X=.40 TO .925 STEP .075
```

```
5890 GOSUB 7370
5900 Lx=Lo*L17
5910 Ld=Lx/D1
5920 Dear=2*Z/PI*Ld
5930 GOSUB 7280
5940 Prod38=Dear*Simp
5950 Sum38=Prod38+Sum38
5960 Ear=.075*Sum38/3
5970 NEXT X
5980 PRINT "EAR=";Ear
5990 Li=L/Ei
6000 FIXED 1
6010 IF (Li<=.10) AND (Li<.15) THEN K1=-1.41246566*Ear^3+1.86397111*Ear^2-.89243
85*Ear+.911195913
6020 IF (Li>=.15) AND (Li<.2) THEN K1=-.61447624*Ear^3+.83127471*Ear^2-.43307547
*Ear+.896822943
6030 IF (Li>=.2) AND (Li<.25) THEN K1=.02225188*Ear^3-.2037164*Ear^2+.09278682*E
ar+.86790735
6040 IF (Li>=.25) AND (Li<.35) THEN K1=-.06496363*Ear^3+.03014274*Ear^2-.0126930
5*Ear+.942830279
6050 IF (Li>=.35) AND (Li<.45) THEN K1=1
6060 IF (Li>.45) AND (Li<.55) THEN K1=1.06
6070 IF Li>.55 THEN K1=.03161495*Ear^3+.02614717*Ear^2+.0064911*Ear+1.09498839
6080 REM IF X=.40 THEN K2=1.08263013*Ear^3-1.33809691*Ear^2+.51828956*Ear+1.2372
29595
6090 REM IF X=.5 THEN K2=.98312312*Ear^3-.8643267*Ear^2+.18894966*Ear+1.49351034
1
6100 REM IF X=.6 THEN K2=1.60347553*Ear^3-1.4680072*Ear^2+.46432209*Ear+1.599596
13
6110 REM IF X=.70 THEN K2=-2.23215188*Ear^3+5.117338*Ear^2-2.36883869*Ear+1.9733
1342
6120 REM IF X=.8 THEN K2=1.257577264*EAR^2-.111323661*EAR+1.598914339
6130 REM IF X=.9 THEN K2=1.399019511*EAR^2-.022698665*EAR+1.561982014
6140 FIXED 3
6150 K2=-2.23215188*Ear^3+5.117338*Ear^2-2.36883869*Ear+1.97331342
6160 PRINT "K1=";K1,"K2=";K2
6170 PRINT SPA(3);"d/l";SPA(5.0);"y";SPA(5.0);"y/l";SPA(4);"(y/l)c";SPA(4);"yc"
6180 DIM B(14)
6190 DATA .0075,.0125,.05,.1,.2,.3,.4,.5,.6,.7,.8,.9,.95,1.0
```

```
6200 FOR I=1 TO 14
6210 READ Dlr
6220 GOSUB 7870
6230 Y=Ymax7*Yymr
6240 Yl=Y/Lo*.70
6250 Ylc=Yl*K1*K2
6260 Yc=Y*Lo
6270 PRINT USING "MD.DDDD,2X,.DDDD,2X,.DDDD,2X,.DDDD,2X,.DDDD";Dlr,Y,Yl,Ylc,Yc
6280 NEXT I
6290 RESTORE 6190
6300 PRINT SPA(3);"X";SPA(3);"TAN Bi";SPA(2);"TAN B";SPA(5.0);"B";SPA(4);"Bi@.7"
;SPA(3);"B@.7";SPA(5.0);"C";SPA(3);"ALPHA";SPA(2);"ALPHA 1";SPA(3);"P/D"
6310 FOR X=.40 TO .925 STEP .075
6320 GOSUB 7460
6330 Tbi=Tbix3
6340 Bi=Bi3
6350 Bi7=ATN(Li/.70)
6360 B7=ATN(101.34*Va/(PI*N*D1*.70))
6370 GOSUB 7370
6380 Lx=Lo*L17
6390 Cl=Clld*D1/Lx
6400 GOSUB 7830
6410 Sbsq7=SIN(B7)^2
6420 Cbib7sq=COS(Bi7-B7)^2
6430 Hh=-.4531250001*(SIN(Bi7)*Lo/(.70*D1))^2+1.1437500001*(SIN(Bi7)*Lo/(.70*D1)
)+1.0025
6440 Hw=10
6450 Ha=33
6460 Hv=.5
6470 Sig7=2*32.1714*(Hw+Ha-Hv)*Sbsq7/((Va*1.689)^2*Cbib7sq)
6480 IF (Sig7>=0) AND (Sig7<=.0368) THEN Ks=-39.4509781*Sig7^2-.980793313*Sig7+.
99966714372
6490 IF (Sig7>.0368) AND (Sig7<=.11) THEN Ks=1.06548319766-4.32647150908*Sig7
6500 Alphal=Ks*(.0849*Cl+.01512*Alpha)
```

```
6510 Alphab=0
6520 Alpha2=Alphab+(Bi7-B7)*(2/(1+COS(Bi7)^2)*(2/Hh-1)-1)
6530 Alpha17=Ks*(.0849*C17+.01512*A7)
6540 Fill=TAN(Bi7+Alpha17+Alpha2)/TAN(Bi7+Alpha17)
6550 Bial=Bi+Alphal
6560 Pdf=PI*X*Fill*TAN(Bial)
6570 PRINT USING "M.DDD,2X,D.DDDD,2X,D.DDDD,2X,.DDDD,2X,.DDDD,2X,.DDDD,2X,.DDDD,
2X,D.DDDD,2X,D.DDDD,2X,D.DDDD";X,Tbix3,Tb,B,Bi7,B7,Cl,Alpha,Alphal,Pdf
6580 NEXT X
6590 PRINT SPA(3);"X";SPA(3);"EPSILON"
6600 FOR X=.40 TO .925 STEP .075
6610 U=Va*1.689*COS(Bi3-B)/SIN(B)
6620 GOSUB 7460
6630 GOSUB 7370
6640 Lx=Lo*L17
6650 Cl=Clld*D1/Lx
6660 GOSUB 7240
6670 IF X=.70 THEN Eps7=Epsolon
6680 Dct=8*Fifteenth*Twelvth*(1-Epsolon*Tbix3)
6690 GOSUB 7280
6700 Fct=Dct*Simp
6710 Sumf=Fct+Sumf
6720 Ctc=.075*Sumf/3
6730 PRINT X;Epsolon
6740 REM   IF X=.70 THEN GOTO 3090
6750 Dcp=(Tbix3+Epsolon)/Tb*8*Fifteenth*Twelvth
6760 GOSUB 7280
6770 Prod72=Dcp*Simp
6780 Sum72=Prod72+Sum72
6790 Cpc=.075*Sum72/3
6800 NEXT X
6810 GOTO 3290
```

```
6820 Eta=Ctc/Cpc
6830 PRINT "Ctc=";Ctc,"Cpc=";Cpc,"ETA=";Eta
6840 Pc=Cpc*D1^2*PI*(Va*1.689)^2*S*(Row/8)/550
6850 PRINT "SHP(absorbed)=";Pc;"AVAILABLE SHP IS";P;"(the propeller can not
 demand more than the available SHP)"
6860 PRINT "THE FOLLOWING GROUP IS FOR Xo=.400 (NOTE ALL MOMENTS ARE IN FT LBS)"
6870 FOR Xo=.40 TO .925 STEP .075
6880 FOR X=.40 TO .925 STEP .075
6890 GOSUB 7460
6900 GOSUB 7370
6910 Lx=Lo*L17
6920 Cl=Clld*D1/Lx
6930 GOSUB 7240
6940 Etbix3=Epsolon*Tbix3
6950 Dmtb=8*Fifteenth*Twelvth*(1-Etbix3)*(X-Xo)
6960 Dmqb=8*Fifteenth*Twelvth*(Tbix3+Epsolon)*(X-Xo)
6970 GOSUB 7280
6980 Fmtb=Dmtb*Simp
6990 Fmqb=Dmqb*Simp
7000 Sum83=Fmtb+Sum83
7010 Sum85=Fmqb+Sum85
7020 NEXT X
7030 Mtb=Row/2*((D1/2)^3*PI/Z)*(1.689*Va)^2*(.075*Sum83/3)
7040 Mqb=Row/2*((D1/2)^3*PI/Z)*(1.689*Va)^2*(.075*Sum85/3)
7050 PRINT "AT Xo=";Xo;"THE BENDING MOMENT IS ";Mtb
7060 PRINT "AT Xo=";Xo;"THE TORSIONAL MOMENT IS ";Mqb
7070 PRINT SPA(3);"X";SPA(8);"Mxo";SPA(10);"Myo"
7080 IF Xo=.40 THEN GOSUB 8300
7090 IF Xo=.475 THEN GOSUB 8320
7100 IF Xo=.55 THEN GOSUB 8340
7110 IF Xo=.625 THEN GOSUB 8360
7120 IF Xo=.70 THEN GOSUB 8380
```

```
7130 IF Xo=.775 THEN GOSUB 8400
7140 IF Xo=.85 THEN GOSUB 8420
7150 IF Xo=.925 THEN GOSUB 8440
7160 GOSUB 7460
7170 Mxo=Mtb*Cbi3+Mqb*Sbi3
7180 Myo=Mtb*Sbi3-Mqb*Cbi3
7190 PRINT USING "M.DDD,2X,DDDDDD.DDDD,2X,DDDDDD.DDDD";X,Mxo,Myo
7200 NEXT X
7210 PRINT "THE FOLLOWING GROUP IS FOR Xo=";Xo+.075
7220 NEXT Xo
7230 GOTO 8760
7240 IF (Cl>0) AND (Cl<.0548) THEN Epsolon=.796*Cl+.569/(Cl*LGT(U*Lx/New)^2.58)
7250 IF (Cl>=.0548) AND (Cl<.2) THEN Epsolon=(2.14*Cl+1.13)*((.40*Cl+.0328)^2/(1
.5708*Cl)+.455/(Cl*LGT(U*Lx/New)^2.58))
7260 IF Cl>=.2 THEN Epsolon=(1.553*Cl+1.25)*(.2025*Cl+.455/(Cl*LGT(U*Lx/New)^2.5
8))
7270 RETURN
7280 IF X=.40 THEN Simp=1
7290 IF X=.475 THEN Simp=4
7300 IF X=.55 THEN Simp=2
7310 IF X=.625 THEN Simp=4
7320 IF X=.70 THEN Simp=2
7330 IF X=.775 THEN Simp=4
7340 IF X=.85 THEN Simp=2
7350 IF X=.925 THEN Simp=4
7360 RETURN
7370 IF X=.40 THEN L17=1.088
7380 IF X=.475 THEN L17=1.086
7390 IF X=.55 THEN L17=1.073
7400 IF X=.625 THEN L17=1.046
7410 IF X=.70 THEN L17=1
7420 IF X=.775 THEN L17=.903
7430 IF X=.85 THEN L17=.763
```

```
7440 IF X=.925 THEN L17=.565
7450 RETURN
7460 Pit3=.70*D1*Tbif*PI
7470 Pd3=Pit3/D1
7480 Li3=.70*Tbif
7490 IF X=.40 THEN Pdr=.984
7500 IF X=.475 THEN Pdr=.9886
7510 IF X=.55 THEN Pdr=.9926
7520 IF X=.625 THEN Pdr=.9962
7530 IF X=.70 THEN Pdr=1
7540 IF X=.775 THEN Pdr=1.0044
7550 IF X=.85 THEN Pdr=1.009
7560 IF X=.925 THEN Pdr=1.0114
7570 Pdix3=Pd3*Pdr
7580 Pit4=D1*Pdix3
7590 Tbix3=Li/X
7600 REM Tbix3=Li3/X THIS GIVES AN OPTIMUM ANGLE BASE ON THE NEW Li.
7610 Bi3=ATN(Tbix3)
7620 Cbi3=COS(Bi3)
7630 Sbi3=SIN(Bi3)
7640 Tb=101.34*Va/(PI*N*D1*X)
7650 B=ATN(Tb)
7660 Cb=COS(B)
7670 Sb=SIN(B)
7680 Sbi3b=SIN(Bi3-B)
7690 Tenth=Sbi3*Sbi3b/Sb
7700 Eleventh=1/Tb
7710 Twelvth=Eleventh-Tenth
7720 Mou=N/60*X/(Va*1.689)
7730 Mouo=N/60/(Va*1.689)
7740 Mou1=Ua*X/(N/60)
```

```
7750 Mouo1=Ua/(N/60)
7760 Wf=Z/(2*PI)*ACS(EXP(-2*(1+Mouo^2)^.5*(1-Mou/Mouo)))
7770 REM Wf1=Z/(2*PI)*ACS(EXP(-2*(1+Mouo1^2)^.5*(1-Mou1/Mouo1)))
7780 Fifteenth=X*Wf*Tenth
7790 Twentith=4*PI*Cbi3/Z
7800 Gamma=2*X*Wf/Z*(1/Ei-1)*(TAN(Bi3)/(TAN(Bi3)^2+1))
7810 Cl1d=2*PI*Gamma*Cbi3/Twelvth
7820 RETURN
7830 IF (Cl>=0) AND (Cl<.0548) THEN Alpha=36.5*Cl
7840 IF (Cl>=.0548) AND (Cl<.2) THEN Alpha=2
7850 IF Cl>.2 THEN Alpha=10*Cl
7860 RETURN
7870 IF Dlr=.0075 THEN Yymr=.01888
7880 IF Dlr=.0125 THEN Yymr=.03244
7890 IF Dlr=.05 THEN Yymr=.14189
7900 IF Dlr=.10 THEN Yymr=.29150
7910 IF Dlr=.2 THEN Yymr=.56636
7920 IF Dlr=.3 THEN Yymr=.78458
7930 IF Dlr=.40 THEN Yymr=.93187
7940 IF Dlr=.5 THEN Yymr=1
7950 IF Dlr=.6 THEN Yymr=.98340
7960 IF Dlr=.70 THEN Yymr=.87797
7970 IF Dlr=.8 THEN Yymr=.68055
7980 IF Dlr=.9 THEN Yymr=.38860
7990 IF Dlr=.95 THEN Yymr=.20650
8000 IF Dlr=1 THEN Yymr=0
8010 IF Dlr=.0075 THEN Fp=-.001326
8020 IF Dlr=.0125 THEN Fp=-.002574
8030 IF Dlr=.05 THEN Fp=-.016816
8040 IF Dlr=.10 THEN Fp=-.039520
8050 IF Dlr=.2 THEN Fp=-.078940
```

```
8060 IF Dlr=.3 THEN Fp=-.097600
8070 IF Dlr=.40 THEN Fp=-.092870
8080 IF Dlr=.5 THEN Fp=-.071780
8090 IF Dlr=.6 THEN Fp=-.037750
8100 IF Dlr=.70 THEN Fp=.005940
8110 IF Dlr=.8 THEN Fp=.056880
8120 IF Dlr=.9 THEN Fp=.112090
8130 IF Dlr=.95 THEN Fp=.139620
8140 IF Dlr=1 THEN Fp=.1669500
8150 IF Dlr=.0075 THEN Np=.001254
8160 IF Dlr=.0125 THEN Np=.001870
8170 IF Dlr=.05 THEN Np=.005704
8180 IF Dlr=.10 THEN Np=.010074
8190 IF Dlr=.2 THEN Np=.017349
8200 IF Dlr=.3 THEN Np=.022222
8210 IF Dlr=.40 THEN Np=.024647
8220 IF Dlr=.5 THEN Np=.025710
8230 IF Dlr=.6 THEN Np=.025853
8240 IF Dlr=.70 THEN Np=.025605
8250 IF Dlr=.8 THEN Np=.024660
8260 IF Dlr=.9 THEN Np=.023047
8270 IF Dlr=.95 THEN Np=.022048
8280 IF Dlr=1 THEN Np=.020937
8290 RETURN
8300 FOR X=.40 TO .925 STEP .075
8310 GOTO 7090
8320 FOR X=.475 TO .925 STEP .075
8330 GOTO 7100
8340 FOR X=.55 TO .925 STEP .075
8350 GOTO 7110
8360 FOR X=.625 TO .925 STEP .075
```

```
8370 GOTO 7120
8380 FOR X=.70 TO .925 STEP .075
8390 GOTO 7130
8400 FOR X=.775 TO .925 STEP .075
8410 GOTO 7140
8420 FOR X=.85 TO .925 STEP .075
8430 GOTO 7150
8440 FOR X=.925 TO .925 STEP .075
8450 GOTO 7160
8460 PRINT "Alpha is the angle of attack"
8470 PRINT "Alphal is the correction to alpha for cavitation"
8480 PRINT "Bi is the hydrodynamic pitch angle"
8490 PRINT "Cl is the coefficient of lift"
8500 PRINT "Cpc is the final power coefficient"
8510 PRINT "Ct is the thrust load coefficient"
8520 PRINT "Ctc is the final thrust load coefficient"
8530 PRINT "Cti is the ideal thrust load coefficient"
8540 PRINT "D is the diameter (ft.)"
8550 PRINT "d is the percent of blade width"
8560 PRINT "EAR is the expanded area ratio (Ae/Ao)"
8570 PRINT "Ei is the ideal propeller efficiency"
8580 PRINT "Epsilon is the drag/lift ratio"
8590 PRINT "Eta is the propeller´s efficiency"
8600 PRINT "G is the circulation"
8610 PRINT "K1 & K2 are the camber correction coefficients"
8620 PRINT "L is the advance ratio (lambda)"
8630 PRINT "Ln is the adjusted advance ratio"
8640 PRINT "Li is the ideal advance ratio"
8650 PRINT "Lo is the blade width at x=0.7"
8660 PRINT "l is the blade width"
8670 PRINT "Mxo is the moment about the x axis"
8680 PRINT "Myo is the moment about the y axis"
8690 PRINT "t is the thickness of the blade element"
8700 PRINT "x is the percent radius of the blade"
8710 PRINT "Wf is the Wilson factor"
8720 PRINT "y is the height of curvature of the blade element"
8730 RETURN
```

```
8740 PRINT "THE COEFFICIENT OF LIFT IS TOO LARGE.  SUGGEST YOU START AGAIN WITH
A LOWER TOTAL RESISTANCE OR INCREASE THE SPEED."
8750 GOTO 20
8760 DISP "THIS IS THE END OF THE RUN.  DO YOU WANT ANOTHER RUN(Y OR N).";
8770 INPUT E$

8780 PRINT "THERE IS NO GROUP FOR Xo=1.0!  THIS RUN IS COMPLETE."
8790 IF E$="Y" THEN 20
8800 IF E$="N" THEN 8810
8810 PRINTER IS 16
8820 PRINT "PROGRAM COMPLETED!"
8830 FIXED 2
8840 END
```

APPENDIX B

SAMPLE COMPUTER OUTPUT

```
The purpose of this program is to determine the following specifications of a
supercavitating propeller:
Diameter (as a function of an assumed RPM)
Blade shape (chord dimensions at various radial stations)
Blade pitch and pitch distribution
Foil camber and thickness distribution
Blade bending moment at radial stations

In order to give you the desired propeller please enter the known
characteristics of the ship followed by pressing CONT.
```

```
Alpha is the angle of attack
Alpha1 is the correction to alpha for cavitation
Bi is the hydrodynamic pitch angle
Cl is the coefficient of lift
Cpc is the final power coefficient
Ct is the thrust load coefficient
Ctc is the final thrust load coefficient
Cti is the ideal thrust load coefficient
D is the diameter (ft.)
d is the percent of blade width
EAR is the expanded area ratio (Ae/Ao)
Ei is the ideal propeller efficiency
Epsilon is the drag/lift ratio
Eta is the propeller's efficiency
G is the circulation
K1 & K2 are the camber correction coefficients
L is the advance ratio (lambda)
Ln is the adjusted advance ratio
Li is the ideal advance ratio
Lo is the blade width at x=0.7
l is the blade width
Mxo is the moment about the x axis
Myo is the moment about the y axis
t is the thickness of the blade element
x is the percent radius of the blade
Wf is the Wilson factor
y is the height of curvature of the blade element
```

```
SHIP'S MAX SPEED IS 80
SHIP'S TOTAL RESISTANCE IS 120000
SHIP'S MAX AVAILABLE SHP IS 45000
THE WAKE FRACTION IS 0
THE THRUST DEDUCTION FACTOR IS 0
NUMBER OF BLADES ON PROPELLER IS 6
THE PERCENT OR FRACTION OF SUBMERGENCE EXPECTED OF THE CRAFT IS .5
ASSUMED RPM IS 600
CALCULATIONS ARE FOR SW
THE ASSUMED WATER TEMPERATURE IS 520.000000
VISCOSITY (NU)= .000013 ft^2/sec



The thrust-load coefficient = .1674
The square root of the thrust-load coefficient is  .4091
The advance coefficient, J = 1.3512
The optimum advance coefficient is 1.2791
The optimum propeller diameter is 10.5634 ft.
The expected efficiency is .6516
The SHP for this optimum propeller is 45240.6829
L = .400            Cti= .160            Ln = .260
The ideal efficiency (Ei) is  .925
Li= .433
   X       TAN Bi     COS Bi      WF         G         C l/D
 .4000    1.0815      .6789     1.2088     .0065      .0294
 .4750     .9107      .7393     1.1596     .0074      .0305
 .5500     .7865      .7860     1.1012     .0080      .0299
 .6250     .6921      .8223     1.0312     .0082      .0281
 .7000     .6130      .8507      .9463     .0030      .0254
 .7750     .5582      .8732      .8407     .0075      .0220
 .8500     .5089      .8912      .7042     .0066      .0178
 .9250     .4677      .9058      .5107     .0049      .0125
THE SUM OF THE PRODUCTS IS 4.387
THE DELIVERED Cti = .122                THE REQUIRED Cti = .160
THE VERIFYING DELIVERED Cti = .2772     THE REQUIRED Cti = .1605
THE VERIFYING DELIVERED Cti = .5545     THE REQUIRED Cti = .1605
THE FINAL TANGENT OF BETA SUB i IS .6206
THAT ANGLE IN DEGREES AT 0.7R IS 31.8238
THE FINAL BETAi HAS BEEN VERIFIED.  YOU MAY PROCEED WITH A CONFIDENCE FACTOR OF
98%.
```

```
Lo= 1.6784

THE APPROXIMATE (WITHIN 30%) EXPANDED AREA RATIO (EAR) IS  .4540

   X      l/l0.7    lx       C1      ALPHA    y/lmax   ymax
 .400   1.0880  1.8262  .1698   2.0000   .0171   .0313
 .475   1.0860  1.8228  .1766   2.0000   .0182   .0331
 .550   1.0730  1.8010  .1753   2.0000   .0180   .0324
 .625   1.0460  1.7557  .1691   2.0000   .0170   .0299
 .700   1.0000  1.6784  .1600   2.0000   .0156   .0262
 .775    .9030  1.5156  .1534   2.0000   .0146   .0221
 .850    .7630  1.2807  .1472   2.0000   .0136   .0174
 .925    .5650   .9483  .1389   2.0000   .0123   .0117

  d/l      y        t/l     t(ft)
  .0075  .0005  .0023  .0039
  .0125  .0003  .0033  .0056
  .0500  .0037  .0087  .0146
  .1000  .0076  .0138  .0232
  .2000  .0148  .0221  .0370
  .3000  .0206  .0288  .0484
  .4000  .0244  .0344  .0578
  .5000  .0262  .0399  .0670
  .6000  .0258  .0457  .0766
  .7000  .0230  .0522  .0875
  .8000  .0178  .0594  .0931
  .9000  .0102  .0640  .1075
  .9500  .0054  .0664  .1115
 1.0000  .0000  .0686  .1151
EAR= .3211
K1= 1.000              K2= 1.666
   d/l      y       y/l     (y/l)c     yc
  .0075  .0005  .0002  .0003  .0008
  .0125  .0008  .0004  .0006  .0014
  .0500  .0037  .0016  .0026  .0062
  .1000  .0076  .0032  .0053  .0128
  .2000  .0148  .0062  .0103  .0249
  .3000  .0206  .0086  .0143  .0345
  .4000  .0244  .0102  .0170  .0410
  .5000  .0262  .0109  .0182  .0440
  .6000  .0258  .0107  .0179  .0432
  .7000  .0230  .0096  .0160  .0386
  .8000  .0178  .0074  .0124  .0299
  .9000  .0102  .0042  .0071  .0171
  .9500  .0054  .0023  .0033  .0091
 1.0000  .0000  .0000  .0000  .0000
   X    TAN Bi   TAN B      B      Bi0.7    B0.7      C     ALPHA   ALPHA i    P/D
 .400  1.0815  1.0179  .7943  .5535  .5268  .1698  2.0000    .0403  1.4644
 .475   .9107   .8572  .7086  .5535  .5268  .1766  2.0000    .0408  1.4653
 .550   .7865   .7403  .6373  .5535  .5268  .1753  2.0000    .0407  1.4672
 .625   .6921   .6515  .5774  .5535  .5268  .1691  2.0000    .0402  1.4697
 .700   .6180   .5817  .5268  .5535  .5268  .1600  2.0000    .0395  1.4727
 .775   .5532   .5254  .4837  .5535  .5268  .1534  2.0000    .0390  1.4769
 .850   .5089   .4790  .4467  .5535  .5268  .1472  2.0000    .0385  1.4817
 .925   .4677   .4402  .4147  .5535  .5268  .1389  2.0000    .0379  1.4861
   X    EPSILON
 .400  .073
 .475  .080
 .550  .080
 .625  .079
 .700  .078
 .775  .077
 .850  .077
 .925  .078
```

```
Li= .433
THE FOLLOWING IS RECALCULATED USING EPSILON!
    X       TAN Bi      COS Bi       WF          G          C 1/D
 .4000     1.0815       .6789     1.2088       .0065       .0294
 .4750      .9107       .7393     1.1596       .0074       .0305
 .5500      .7865       .7860     1.1012       .0080       .0299
 .6250      .6921       .8223     1.0312       .0082       .0281
 .7000      .6180       .8507      .9463       .0080       .0254
 .7750      .5582       .8732      .8407       .0075       .0220
 .8500      .5089       .8912      .7042       .0066       .0178
 .9250      .4677       .9058      .5107       .0049       .0125
THE SUM OF THE PRODUCTS IS 4.887
THE DELIVERED Cti = .122                   THE REQUIRED Cti = .161
THE VERIFYING DELIVERED Cti = .2790        THE REQUIRED Cti = .1608
THE VERIFYING DELIVERED Cti = .5561        THE REQUIRED Cti = .1608
THE FINAL TANGENT OF BETA SUB i IS .6206
THAT ANGLE IN DEGREES AT 0.7R IS 31.8250
THE FINAL BETAi HAS BEEN VERIFIED.  YOU MAY PROCEED WITH A CONFIDENCE FACTOR OF
98%.
Ctc= .1160              Cpc= .1464              ETA= .7923
SHP(absorbed)= 212.9514 AVAILABLE SHP IS 45000.0000 (the propeller can not
demand more than the available SHP)
THE FOLLOWING GROUP IS FOR Xo=.400 (NOTE ALL MOMENTS ARE IN FT LBS)
AT Xo= .4000 THE BENDING MOMENT IS  50535.5667
AT Xo= .4000 THE TORSIONAL MOMENT IS  34183.8510
   X         Mxo          Myo
 .400    59407.6102   13896.5829
 .475    60380.0900    8753.5083
 .550    60854.3779    4373.0844
 .625    61007.8108     652.8375
 .700    60959.5444   -2512.5919
 .775    60787.7514   -5218.0882
 .850    60543.0925   -7544.0786
 .925    60258.1747   -9556.7543
THE FOLLOWING GROUP IS FOR Xo= .4750
AT Xo= .4750 THE BENDING MOMENT IS  88811.5335
AT Xo= .4750 THE TORSIONAL MOMENT IS  59049.1160
   X         Mxo          Myo
 .475  105421.6572   16141.8945
 .550  106311.7099    8491.5793
 .625  106631.7185    1990.7759
 .700  106591.4329   -3543.0232
 .775  106328.8192   -8274.5858
 .850  105933.5517  -12343.7920
 .925  105463.5488  -15865.8893
THE FOLLOWING GROUP IS FOR Xo= .5500
AT Xo= .5500 THE BENDING MOMENT IS  114827.9004
AT Xo= .5500 THE TORSIONAL MOMENT IS  74595.7943
   X         Mxo          Myo
 .550  136371.9960   12355.4846
 .625  136871.7231    4013.8152
 .700  136895.6654   -3091.2938
 .775  136623.2034   -9169.4928
 .850  136171.3775  -14399.1404
 .925  135616.1224  -13927.4050
THE FOLLOWING GROUP IS FOR Xo= .6250
AT Xo= .6250 THE BENDING MOMENT IS  128584.6674
AT Xo= .6250 THE TORSIONAL MOMENT IS  80823.3875
   X         Mxo          Myo
 .625  151727.8247    6721.9553
 .700  151872.2420   -1157.4038
 .775  151670.9039   -7902.8091
 .850  151256.5700  -13710.1237
 .925  150715.8953  -18741.3015
```

```
THE FOLLOWING GROUP IS FOR Xo= .7000
AT Xo= .7000 THE BENDING MOMENT IS  130081.8345
AT Xo= .7000 THE TORSIONAL MOMENT IS  77733.3941
   X        Mxo          Myo
 .700  151521.1627    2258.6468
 .775  151471.9207   -4474.5349
 .850  151189.1292  -10276.7420
 .925  150762.8676  -15307.5787
THE FOLLOWING GROUP IS FOR Xo= .7750
AT Xo= .7750 THE BENDING MOMENT IS  119319.4017
AT Xo= .7750 THE TORSIONAL MOMENT IS  65324.3146
   X        Mxo          Myo
 .775  136026.2539    1115.3300
 .850  135969.0551   -4098.9951
 .925  135757.0394   -8626.2366
THE FOLLOWING GROUP IS FOR Xo= .8500
AT Xo= .8500 THE BENDING MOMENT IS  96297.3690
AT Xo= .8500 THE TORSIONAL MOMENT IS  43596.6491
   X        Mxo          Myo
 .850  105596.3476    4823.1168
 .925  105698.4106    1302.7247
THE FOLLOWING GROUP IS FOR Xo= .9250
AT Xo= .9250 THE BENDING MOMENT IS  61015.7364
AT Xo= .9250 THE TOPSIONAL MOMENT IS  12550.3974
   X        Mxo          Myo
 .925   60586.9812   14479.3054
THE FOLLOWING GROUP IS FOR Xo= 1.0000
THERE IS NO GROUP FOR Xo=1.0!  THIS RUN IS COMPLETE.
```

APPENDIX C

SAMPLE CALCULATIONS

Calculations have been made at the seventy percent radial station (x = 0.7) in both manual and computer modes with the following input data:

Maximum Velocity	80 kts (Design Point)
Power Available	45,000 SHP
Ship Resistance	120,000 lbs
Propeller Speed	600 RPM
Submergence	0.5
Wake Fraction	0.0
Number of Blades	6
Density	2.0 (Salt Water)

CALCULATIONS

LINE	PARAMETER	COMPUTER	MANUAL
570	D	9.17	9.2 ft
640	V_a	80 kts	80 kts
650	T	120,000 lbs	120,000 lbs
660	C_t	0.1162	0.1162
720	J	1.126	1.126
740	$J_{opt} = J1$	1.279	1.28
790	D_1	10.563 ft	10.56 ft
880	L	0.400	0.407
890	C_{to}	0.150	0.153
900	C_{ti}	0.160	0.164

LINE	PARAMETER	COMPUTER	MANUAL
3250	E_i	0.975	0.922
3290	L_i	0.433	0.4414
3420	T_{bi}	0.618	0.6306
3430	T_b	0.5817	0.582
3440	B	0.527	0.527
3720	Mou	0.0518	0.0518
3730	Mouo	0.00740	0.00740
3770	Wf	0.9463	0.9463
4350	C_{tidl}	0.122	0.1675

Note: The manual value is based on but one point, while the computer program is based on ten points.

LINE	PARAMETER	COMPUTER	MANUAL
5360	C_{irc}	0.0080	0.0084
5370	C_{lldl}	0.0254	0.0266
5420	L_0	1.678 ft	1.756 ft
5480	C_l	0.16	0.16
5710	Y_{lmax}	0.0156	0.0156
5720	Y_{max}	0.0230	0.0274
5820	Y	0.0230	0.0274
5830	T_{lr}	0.0522	0.0399
5960	Ear	0.3211	0.3200
6150	K_2	1.6666	1.70
6160	K_1	1.000	1.04
6240	Y_1	0.0096	0.0109
6250	Y_{1c}	0.0160	0.0193
6260	Y_c	0.0386	0.0339

LINE	PARAMETER	COMPUTER	MANUAL
6500	Alpha_1	0.0395	0.0394
6560	Pdf	1.4727	1.56
6690	Eps7	0.078	0.078
6720	C_{tc}	0.116	0.155
6820	Eta	0.79	0.78

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